Integrated Farming Systems for Food and Energy in a Warming, Resource-depleting World

D i s s e r t a t i o n

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Dedication

... With love and admiration

To those who have ability and commitment, those who are involved and make the dream a reality, those who work hard in the search for and construction of alternatives, those who value and potentiate integrated sustainable development from and towards all fields.

…With respect

To those who have not decided and / or discovered the ability to bring forward alternatives of their own, internal and external to ratify and revitalize their potentialities towards sustainable development and to get better ways of personal and collective life.

….With hope

To those who consciously or unconsciously support other people's decisions and their models, delivering their capabilities, potentials and dreams and compromising their offspring (genetic or otherwise) to continue along the same path

To those who have lost their sense of wonder

With endless love and gratitude to Thomas, to our beloved daughter Sofia , to my parents: German and Chelita, to my sister Monica, to my niece Ana Maria and my great friend Patricia who have been fundamental in the process of personal and professional training. Thanks for their encouragement, support and love.

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Thanks to all those who in one way or another have been involved in seeking fairer, alternative lives from every point of view: social, economic and environmental.

I invite you to continue working hard in the search of better alternatives and make the decision to move from talk about sustainable development to "live, work and build sustainable development in your own lives”.

General Summary

Summary

This thesis is a contribution to the strategy that should underpin all future farming systems: namely the need to “de-carbonize” the system, by reducing emissions of greenhouse gases, generating electricity locally from natural resources, making maximum use of solar energy and ensuring there is no conflict between use of available resources for both food and fuel production. All the experiments described in the thesis were carried out in the period 2005 - 2009 at the ecological farm (TOSOLY) of the UTA Foundation (Fundación para la Producción Agropecuaria Tropical Sostenible Capitulo Colombia – UTA) of which the principals are Dr T R Preston (President) and MSc Lylian Rodríguez (Director).

The thesis is developed in a series of 11 chapters. The papers that are presented in Chapters 3, 4, 5, 6, 8, 9, 10 and 11, have all been published. Chapter 11 is a general discussion of the major findings of the research and its implications for the design of future farming strategies.

Chapter 1 reviews the role of energy, especially that derived from fossil fuel, as the motor of development and population growth, and the cause of the economic crisis of 2008-09. The inevitable decline in the production of oil (peak oil), which will have negative effects on all features of contemporary lifestyles, is viewed from the positive standpoint of the opportunities that will be created for more sustainable farming systems when solar energy, via the production of biomass, will be the basis of the required needs for food, feed and fuel energy. It is argued that in such a scenario, small scale integrated family farms will have comparative advantages- economic, social and environmental - in a world in the decline phase of the oil age and increasing dependence on solar energy. Transport is the major end user of fossil fuel, thus as the supply of this resource diminishes - and the price increases - there will be advantages in decentralization and localization of both production and processing of the immediate products of photosynthesis which are of low bulk density and therefore expensive to transport. An analysis of the alternative technologies for production of fuel energy from biomass, as a component of a farming system, leads to the conclusion that gasification is the most appropriate route. The advantages of this process are that: the feedstock is the fibrous parts of plants which are not viable sources of food or feed. The energy used to drive the process is derived from the combustion of the feedstock and there is minimal input of external sources energy (mainly for the construction of the gasifier and associated machinery). The products of gasification are a combustible gas and a carbon-rich residue (biochar). The gas can be used to drive an internal combustion engine linked to an alternator producing electricity; while the biochar when returned to the soil can be a sink for sequestering carbon and a means of improving soil fertility. The role of livestock in the farming system is emphasized as the means of optimizing the use of highly productive perennial crops such as sugar cane and multi-purpose trees. Sugar cane is easily separated into energy-rich juice - which can replace cereal grains in feeding of pigs - and residual bagasse which is one of the feedstocks of the gasifier. Forage trees are the natural feed resources for goats which selectively consume the leaves, leaving the fibrous stems as another feedstock for gasification. Sugar cane juice contains no fibre and almost no protein which creates opportunities for use of vegetative sources of protein such as the foliage of perennial plants, among which New Cocoyam (*Xanthosoma sagittifolium*) has been found to have many advantages. The Chapter concludes with emphasis on the advantages of small scale farming systems where there is close integration among crops, trees, animals and people, with recycling of all wastes.

Chapter 2 provides an overall description of the farm and its principal activities. The farm occupies 7 ha of sloping land (average slope of 20%) in the Colombian foothills (1500 masl) in the Department "Santander Sur", 20 km from the town of Socorro. The region is characterized by relatively uniform rainfall (2800 mm in 2008) and soils that are acidic (pH 4.0-4.5). Traditionally the soils in the region have been, and continue to be, exploited for shade "Arabica" coffee and small scale production of "Panela" from sugar cane. The principal crop is sugar cane presently occupying 1.34 ha but projected to increase to 2 ha as the pasture areas are gradually displaced with more productive crops. Tree crops include coffee, cocoa, and forage trees (Mulberry [*Morus alba*], Mexican Sunflower [*Tithonia diversifolia*], forage plants (New Cocoyam [*Xanthosoma sagittifolium*] and Water spinach [*Ipomoea aquatica*] and trees for timber, fuel and shade for coffee. The livestock and fuel components are chosen for their capacity to utilize the crops and byproducts produced on the farm. Sugar cane stalk is fractionated into juice and residual bagasse. The tops including the growing point and some whole stalk are the basal diet for dual purpose cattle and a component of the diet of the goats. The juice is the energy feed for pigs and the source of "sweetener" for the family. The forage trees are the basal diet of the goats that consume the leaves, fine stems and bark as sources of protein. The bagasse from the sugar cane and the residual stems from the forage trees are the fuel source for a down-draft gasifier that provides a combustible gas for an internal combustion engine linked to an electrical generator. Foraging hens play a dual-purpose role in controlling the weeds in the forage tree plots and producing eggs and meat. A horse is used to transport the sugar cane and forages. All high moisture wastes (pig and human excreta, waste water from coffee pulping, washing of dishes and clothes) are recycled through plug-flow, tubular plastic (polyethylene) biodigesters. Effluents from the biodigesters and manure from the goats and cattle are recycled to the crops as fertilizer. No chemicals are used on the farm other than those that are components of the rumen supplement fed to the cattle (urea, rock phosphate, lime and salt).

The research presented in Chapter 3 investigated the potential to use the leaves of the New Cocoyam plant as a replacement for soybean in the feeding of pigs. Twelve pigs in 4 pens (3 animals in each) were used to compare two treatments in a completely random design with 2 repetitions. The treatments were soybean meal at 500 g/animal/day (control) and fresh leaves of New Cocoyam (4 kg/animal/day and 250 g/animal/day of soybean meal). The rest of the diet was sugar cane juice and a mineral supplement. The trial lasted 56 days during the growth phase from 25 to 56 kg live weight. There were no differences between treatments for the parameters: DM intake, live weight gain and feed conversion, the values of which were within the range normally observed for this type of diet. It was concluded that fresh leaves of New Cocoyam leaves could replace at least half the soybean protein in diets based on sugar cane juice for growing pigs.

The use of New Cocoyam leaves as the only protein source in pig diets was the subject of the research described in Chapter 4. The four treatments applied to 4 growing pigs in a 4*4 Latin square arrangement were levels of fresh leaves of New Cocoyam (NC) equivalent to 0, 30, 60 and 100% substitution of the protein from soybean meal in a basal diet of fresh sugar cane juice. The pigs were crossbred castrated males (Yorkshire*Landrace*Pietrain) with initial weight of 13.4±0.54 kg. They were maintained in metabolism cages made from wood and bamboo. Experimental periods were of 14 days with collection of faeces and urine during the last 5 days of each period. There were significant effects of N intake on DM intake, urine N excretion, and N retention. Adjusting the data for these variables by covariance for differences in N intake changed markedly the treatment effects on DM intake and N retention. After adjustment, DM intake was highest for NC100 and lowest for NC0, while N retention was similar on all diets. N retention as a proportion of the N digested was higher on the diets containing Cocoyam leaves. Apparent OM digestibility declined from 920 to 808 and that of crude protein from 820 to 608 g/kg for the diets with increasing proportions of Cocoyam leaves. It was concluded that the protein in fresh Cocoyam leaves has a high biological value and that the limiting nutritional factor is the lower digestibility of the protein compared with soybean meal.

The research described in Chapter 5 aimed to define the shape of the response curves in production parameters when varying levels of New Cocoyam leaves were fed as the sole supplement to the basal diet of sugar cane juice.

Four crossbred (Yorkshire*Landrace*Pietrain) castrated male pigs with initial weight of 18.7±3.2 kg received varying proportions of ensiled New Cocoyam leaves (ENCL) and fresh sugar cane juice in two consecutive periods to provide different levels of crude protein in the range of 80 to 160 g/kg of diet DM. In period 1, the planned levels were: 100, 120, 140 and 160 g/kg DM; in period 2 these were changed to 90, 110, 130 and 150 g/kg DM. The fresh sugar cane juice contained 20 to 21% total sugars. The Cocoyam leaves were macerated in a high-speed mechanical chopping machine and ensiled with addition of 10% (fresh basis) of sugar cane juice. The leaf silage was of excellent quality as judged by smell and colour and the rapid fall in pH (< 4) within 3 days of ensiling the leaves. Recorded proportions of ENCL in diet DM were 0.49, 0.56, 0.67 and 0.76 in period 1 and 0.46, 0.48, 0.57 and 0.67 in period 2. DM intake was high on all diets (range from 32 to 53 g/kg LW) and showed a curvilinear response to increasing proportions of ENCL in the diet, with a maximum value at 0.55 of ENCL in diet DM. Apparent digestibility of DM decreased, and that of crude protein increased, as the proportion of ENCL in the diet DM increased. N retention increased with increasing proportion of ENCL in the diet, the relationship being curvilinear with the maximum value at 0.67 ENCL, equivalent to 130 g crude protein per kg of diet DM.

The hypothesis that was tested in the study presented in Chapter 6 was that there would be a synergistic response in growth of maize when biodigester effluent, rich in NH_4-N, was combined with biochar, derived by gasification of sugar cane bagasse. Two experiments were carried out to measure changes in soil fertility as a function of the growth of maize plants over a 30-40 day period following seeding. In each experiment a completely randomized design was used with 4 replications of the treatments applied to samples of soil held in one litre capacity plastic bags. In experiment 1, 8 treatments were compared in a 2*2*2 factorial arrangement. The factors were: with or without biochar at 50g/kg soil; fertile soil or sub-soil; and with or without biodigester effluent (100 kg N/ha). In experiment 2, ash from a wood-burning stove replaced the biochar used in experiment 1. Biochar increased green biomass growth of the maize on the fertile soil in absence or presence of biodigester effluent and in the sub-soil when effluent was applied, but had no effect on heavily leached soil without effluent. Application of effluent had no effect on green biomass growth in the fertile soil irrespective of the presence or not of biochar. By contrast, the effluent dramatically increased green biomass growth when biochar was applied to the sub-soil but had no effect in the absence of biochar. Effects on growth of the roots mirrored those on the green biomass except in the case of the sub-soil without effluent when the biochar markedly increased root growth. Soil pH was increased from 4-4.5 to 6.0-6.5 due to addition of biochar. Wood ash brought about increases in the weight of both the aerial part and roots of the maize but the relative increases were only half of those observed when biochar was used. Soil pH was increased to values between 9 and 10. It was concluded that there are synergistic effects on plant growth in heavily leached, acid soils when biodigester effluent is combined with biochar produced by gasification of sugar cane bagasse.

In the research described in Chapter 7, a randomized block design was employed to compare the effect of choice of planting material on the biomass yield of New Cocoyam. The sources of planting material were suckers taken from the base of the root or sections of the disk taken from the stem. There were 4 replications of each treatment arranged in 2 blocks in each of the two locations in the farm. Plant spacing was 70 cm between rows and between plants in the row. Establishment of the plants was on 15 September 2006. Harvesting of leaves and petioles began on 18 February 2007 and continued at approximately 30 day intervals until 3 October 2007. Fresh biomass (leaves and petioles) yields were 50% greater when the plants were established from suckers than from disks. The yields from plants established from suckers were equivalent to 128 tonnes/ha/yr fresh biomass, 14.5 tonnes DM and 1.90 tonnes crude protein/ha/yr. More leaves were produced from plants established from disks than from suckers but they were much smaller. More suckers were produced by plants established from disks than from suckers, but the overall development of the plants was in favour of those established from suckers. On a DM basis, the leaves accounted for 60% of the biomass and 87% of the crude protein.

The results of ensiling the combined leaves and petioles of New Cocoyam were studied in the research note described in Chapter 8. Complete leaves and petioles of New Cocoyam were harvested from 40 plants grown in the TOSOLY farm in Santander province, Colombia. Ten plants were separated into leaves and stems, which were weighed and then each chopped finely with a knife to give representative samples of leaves and petioles, which were taken for analysis for DM, N and ash. The other 30 plants were macerated in an ensiling machine and the macerated product thoroughly mixed and enclosed in 28 air-tight plastic containers of 200 ml capacity. Four samples were allocated for analysis on each of days 0 (before ensiling), 1, 2, 3, 4, 5 and 7 days later. The containers were kept at ambient temperature in an enclosed room. DM and crude protein contents of fresh petiole (7.3 and 5.2%) were much lower than in the fresh leaf (17 and 18% in DM), but sugars were higher (38 and 20% in DM). On a fresh basis, there was twice as much biomass in the petiole than in the leaf, but these proportions were reversed in terms of DM. The pH fell from 5.81 in the fresh mixture of leaf+petiole to 4.37 within 24 h, and to 3.98 in 48 h. Lactic acid reached 2.07% in DM after 7 days of ensiling.

Practical experience from commercial use of the gasifier in the TOSOLY farm was reviewed in the study reported in Chapter 9. The feed stocks used in the down-draft "Ankur" gasifier were sugar cane bagasse and mixed stems of Mulberry (*Morus alba*) and Tithonia (*Tithonia diversifolia*). The tests were done under commercial conditions over an extended period (90 days). The bagasse was the by-product of the extraction of the juice from sugar cane stalks, which was fed to pigs; the stems were the residues after the leaves and (in the case of the Mulberry) the rind had been consumed by confined goats The 10KW gasifier (Ankur WBG10) was imported from India. Rates of consumption of the feedstock were similar for the bagasse and the stems (4.32 and 4.65 kg DM/h). The stems produced a greater percentage of biochar (11.7% of the DM in the feedstock) than the bagasse (8.5%). Management of the gasifier was simpler in the case of the stems as these flowed more easily in the hopper, whereas the bagasse tended to “bridge” requiring frequent agitation to maintain the gas flow. It was estimated that the bagasse from the 1.5 ha of sugar cane required to feed a constant population of 45 pigs (about 50 kg DM daily), and the 1ha in forage trees for 20 breeding goats, could provide electrical energy yields of 50 KWh daily. The biochar residue (35% ash; 65% carbon) from the gasification of the bagasse and tree stems would be sufficient to condition 0.1 ha of crop land annually with the potential to sequester annually up to 5.4 tonnes of carbon dioxide.

The aim of the study presented in Chapter 10 was to measure the Energy Return on Energy Invested (EROEI) in TOSOLY farm in which: (i) fibrous crop byproducts (sugar cane bagasse and stems from forage trees) are used as feedstock to produce " producer" gas in a down-draft gasifier; and (ii) all high moisture organic wastes from pigs and the farm family are fed into a biodigester to produce biogas. The hypothesis was that the production of a combustible gas from biomass (gasification), when conducted as part of an integrated farming system involving livestock, would have a much higher EROEI, and be more environmentally friendly, than the production of other biofuels, especially ethanol production from maize and other "edible" carbohydrates. In the farming system, sugar cane (1.5ha produces 120 tonnes stalks) supplies the energy (sugar cane juice) to feed a constant population of fattening 40 pigs. Forage trees (1 ha planted with Mulberry and *Tithonia diversifolia*) provide the protein (as leaves) for 20 adult goats and progeny. The residual bagasse (18 tonnes DM/year) from the sugar cane and the stems from the forage trees (6 tonnes DM/year) are the feedstock for the gasifier. Annual outputs are 221,760 MJ as producer gas and 40,150 MJ as biogas. Daily production of electricity from an IC gas engine and alternator is 54.7 KWh from the producer gas and 8 KWh from the biogas, the total exceeding six-fold the daily electricity requirements of the farm. Annual indirect (embedded) energy costs were estimated to be 33,205 MJ with 34% derived from human muscle power and 30% from purchased animal feeds. The output of 261,910 MJ as combustible gas results in an EROEI of 8:1.

Finally in Chapter 11, the overall findings of the thesis are discussed in relation to the proposed strategy that: f*uture farming systems should respond to the need to "de-carbonize" the system, by reducing emissions of greenhouse gases, generating electricity locally from natural resources, making maximum use of solar energy and ensuring there is no conflict between use of available resources for both food and fuel production*.

It was concluded that:

- The ensiled foliage (combined leaves and petioles) of the New Cocoyam plant (*Xanthosoma sagittifolium*) offers a high degree of promise as a protein-rich forage for replacing conventional protein sources in diets for pigs
- Integrated, small scale, farming systems based around multi-purpose crops and livestock, can provide food, feed and fuel energy with no conflict among these end uses
- Gasification of fibrous crop residues produces electricity and a soil conditioner (biochar) that is also a sink for sequestration of atmospheric carbon. Bio-digestion of all liquid wastes produces a gaseous fuel for cooking with alternative use as a complement to the gaseous fuel from the gasifier.
- The system delivers real benefits for the environment (a negative carbon footprint) through carbon sequestration and improvements in soil fertility.

Keywords: Biochar, biodigesters, biomass, carbon footprint, carbon sequestration, cattle, climate change, electricity, energy, EROEI, feedstock, fossil fuel, gasification, global warming, goats, greenhouse gas emissions, live stock, pigs, soil fertility, sustainable farming systems.

Allgemeine Zusammenfassung

Diese Arbeit ist ein Beitrag zur Entwicklung einer Strategie für die eine CO_2 sparende zukünftige Landwirtschaft, in der nur geringe Emissionen von Treibhausgasen entstehen, die Stromerzeugung vor Ort aus natürlichen Ressourcen erfolgt, eine maximale Ausnutzung der Sonnenenergie genutzt wird, und der Konflikt zwischen der Nutzung der verfügbaren Ressourcen für Nahrungsmittel und Treibstoff Produktion vermieden wird. Alle Versuche in der Arbeit wurden in den Jahren 2005 -2009 auf der Öko-Farm (TOSOLY) der UTA (Fundación para la Producción Agropecuaria Tropical Sostenible Capitulo Kolumbien - UTA) unter der Leitung von Dr. TR Preston (Präsident) und MSc Lylian Rodríguez (Director) durchgeführt.

Die Thesis enthält insgesamt 11 Kapitel. Die Kapitel 3, 4, 5, 6, 8, 9 und10 sind veröffentlicht. Kapitel 11 ist eine allgemeine Diskussion über die wichtigsten Erkenntnisse der Forschung und ihrer Implikationen für die Gestaltung der künftigen Strategien für die Landwirtschaft.

Kapitel 1 bietet einen Überblick über die Rolle der aus fossilen Brennstoffen gewonnen Energie, als der Motor der bisherigen Entwicklung, des Bevölkerungswachstums und als einer der Ursachen der Wirtschaftskrise von 2008-09. Die unvermeidlichen Rückgang der Produktion von Erdöl mit den negativen Auswirkungen auf alle Aspekte des heutigen Lebensstil, wird als eine positive Herausforderung für nachhaltigere Landwirtschaftssysteme angesehen, in denen Solarenergie, über die Produktion von Biomasse, die energetische Grundlage für die Erzeugung von Lebensmittel, Futtermittel und Brennstoff-Energie liefert. Es wird argumentiert, dass in einem solchen Szenario, kleine integrierte Familienbetriebe über komparative wirtschaftliche, soziale und ökologische Vorteile in einer Welt verfügen, die durch die Verknappung von fossilen Energieträgern und einer zunehmenden Abhängigkeit von Solarenergie geprägt wird. Das Transportwesen ist einer der größten Nutzer von fossilen Brennstoffen und bei einer mit der Verknappung einhergehenden Preiserhöhung werden Vorteile der Dezentralisierung und Lokalisierung von Produktion und Verarbeitung der unmittelbaren Produkte der Photosynthese wirksam, besonders für jene mit niedriger Energiekonzentration und daher geringer Transportwürdigkeit. Eine Analyse der alternativen Technologien für die Produktion von Brennstoffen aus Biomasse in zukünftigen Landwirtschaftssystemen, führt zu dem Schluss, dass die Nutzung von Biogas der günstigste Verwertungsweg ist. Die Vorteile dieses Verfahrens liegen in der Nutzung von nachwachsenden rohfaserreichen Pflanzen, die nicht primär als Futter- oder Nahrungsquelle dienen. Die Produkte der Vergasung sind ein brennbares Gas und ein kohlenstoffreicher Rückstand (Biochar). Das Gas kann zur Stromerzeugung genutzt werden, während das Biochar bei Rückführung in den Boden eine Senke für Kohlenstoff-Sequestrierung und ein Mittel zur Verbesserung der Bodenfruchtbarkeit darstellt.

Die Viehhaltung in der integrierten Landwirtschaft dient der Optimierung des Einsatzes von hoch produktiven mehrjährigen Kulturpflanzen, wie Zuckerrohr-und Mehrzweck-Bäume. Der energiereiche Saft vom Zuckerrohr wird als Getreideersatz in der Fütterung von Schweinen eingesetzt, und die Bagasse bildet den Rohstoff für die Biogasgewinnung. Futter Bäume sind die natürlichen Futtermittel-Ressourcen für Ziegen, die selektiv die Blätter verbrauchen, so dass die faserreichen Pflanzenteile als weiteres Ausgangsmaterial für die Biogasgewinnung zu verwenden sind. Zuckerrohr-Saft enthält keine Ballaststoffe und Protein, sodass Möglichkeiten für den Einsatz andrerer proteinreicher Pflanzen bestehen, wie z.B. Blattmasse von mehrjährigen Futter-Pflanzen, darunter die neue Cocoyam (Tannia).

Das Kapitel unterstreicht die Bedeutung der Vorteile der kleinen landwirtschaftlichen Systeme, mit enger Nutzungsintegration zwischen Ackerkulturen, Futter-Bäumen, Tierhaltung und selbst häuslichen Abfällen.

Kapitel 2 enthält eine Beschreibung des Untersuchungsbetriebes und seiner Hauptaktivitäten. Die Farm verfügt über 7 ha Hangflächen mit einem durchschnittlichen Gefälle von 20% in der kolumbianischen Vorgebirgsregion auf 1500 m ü.NN in der administrativen Region "Santander Sur", 20 km von der Stadt Socorro. Die Region ist gekennzeichnet durch relativ einheitliche Niederschläge (2800 mm im Jahr 2008) und saure Böden (pH 4.0-4.5). Traditionell Landnutzung ist Kaffeeanbau und Zuckerroh. Auf dem Betrieb wird Zuckerrohr auf 1,34 ha mit einer Projektion auf 2 ha angebaut und verdrängt sukzessive die traditionelle Weide. Weitere Anbaukulturen sind Kaffee, Kakao, Futterbäume (Maulbeerbaum [Morus alba], mexikanische Sonnenblume [Mexikanische Sonnenblume], Futterpflanzen (New Cocoyam [Tannia] und Wasserspinat [Ipomoea aquatica] sowie Bäume für Holz-, Kraftstoff- und Schatten für Kaffee. Die gehaltenen Tierarten und die Energielieferanten sind gemäß ihrer Fähigkeit zur Nutzung von Neben- und Abfallprodukten ausgewählt. Das Zuckerrohr wird in Saft und Restbagasse aufgetrennt. Die Zuckerrohrspitzen einige ganze Zuckerrohrpflanzen sind die Grundration für Mehrnutzungsrinder und ein Bestandteil der Ernährung der Ziegen. Der Saft ist der Energielieferant für Schweine und die Süßstoffquelle für die Familie. Blätter und Rinden der Futter Bäume stellen das proteinreiche Grundfutter für die Ziegen. Die Bagasse aus Zuckerrohr und der Rest der Futterbäume bilden die Materialgrundlage für die Biogasanlage, die brennbares Gas für eine Wärme-Kraftmaschine zur Erzeugung von Elektrizität. Freiland-Hühnerhaltung dient einem zweifachen Zweck zur Kontrolle des Unterbewuchses auf den Futterbaumflächen. und Erzeugung von Eiern und Fleisch. Ein Pferd wird verwendet, um das Zuckerrohr und Futter zu transportieren. Alle Abfälle mit hohem Feuchtgehalt (Abprodukte vom Schwein und Haushalt, Abwasser aus der Kaffeebearbeitung werden in einem Schlauch-Biodigester genutzt (Plug-flow-Recycling-, Polyethylen biodigesters). Abwässer aus dem Biodigesters und Gülle aus der Tierhaltung werden als Pflanzendünger verwertet. Chemikalien werden auf dem Hof mit Ausnahme solcher für die Pansenoptimierung der Wiederkäuer (Harnstoff, Rohphosphat, Kalk und Salz) nicht verwendet.

In Kapitel 3 wird das Potenzial der Nutzung von New Cocoyam Blättern als Ersatz für Soja in der Fütterung von Schweinen untersucht. Das Versuchsdesign beinhaltete zwölf Schweine in 4 Gruppen (3 Tiere in jeder) mit zwei Wiederholungen und randomisierter Zuordnung. Die Futterbehandlungen waren Sojaschrot mit 500 g / Tier / Tag in der Kontrolle und frische New Cocoyam Blätter (4 kg / Tier / Tag) und Sojaschrot (250 g / Tier / Tag). Der Rest der Diät war Zuckerrohr-Saft und ein Mineralzusatz. Der Versuch dauerte 56 Tage während der Wachstumsphase von 25 bis 56 kg Lebendgewicht. Es gab keine Unterschiede zwischen den Behandlungen für die Parameter: DM Aufnahme, Lebendgewichtszunahme und Futterverwertung. Alle Werte entsprachen den Normbereichen. Eine Verfütterung von frischen New Cocoyam Blättern könnte mindestens die Hälfte der Soja-Protein in einer Rationen auf der Basis von Zuckerrohr-Saft für die Mast von Schweinen ersetzen.

Die Nutzung der neuen Cocoyam Blätter als einzige Proteinquelle in der Schweinefütterung war das Thema der Forschung in Kapitel. In den vier Behandlungen mit 4 wachsenden Schweinen angelegt als ein komplettes 4 * 4 lateinisches Quadrat variierte die Frischblattmenge von New Cocoyam (NC) von 0, 30, 60 und 100% ige Substitution des Proteins aus Sojamehl in einer Basalration von frischem Zuckerrohrsaft. Die Schweine waren Kastraten einer Kreuzung von Yorkshire * Landrasse * Pietrain mit einem Anfangsgewicht von 13,4 ± 0,54 kg und wurden über 14 Versuchstage in Stoffwechselkäfigen gehalten. Die

Sammlung von Kot und Urin erfolgte in den letzten 5 Tagen des jeweiligen Versuchszeitraums. Es bestanden signifikante Einflüsse der N-Aufnahme auf die Trockenmasseaufnahmen, die N-Ausscheidung im Harn und die N-Retention. Eine Korrektur der Daten für diese Variablen durch Berücksichtigung der Kovarianz führte zu einer markanten Veränderung des Behandlungseffekte auf TrM-Aufnahme und N-Retention Nach Korrektur bestand die höchste bzw. niedrigste TrM-Aufnahme in der 100NC –Behandlung bzw. der NC0-Behandlung, während die N Retention keine Unterschiede zwischen Behandlungen aufwies. Die N Retention als Anteil des verdauten N war höher in den Behandlungen mit Cocoyam Blätter. Die Scheinbare OM Verdaulichkeit sank von 920 bis 808 und die des Rohproteins von 820 bis 608 g / kg bei den Rationen mit steigendem Anteil der Cocoyam Blätter. Es wurde festgestellt, dass das Protein in frischem Cocoyam zwar eine hohe biologische Wertigkeit aber eine geringere Verdaulichkeit als das Soja-Protein aufweist.

In Kapitel 5 wird der Reaktionsverlauf einer Fütterung mit unterschiedlichem Anteil von New Cocoyam Blättern als einzige Ergänzung zur Basalration von Zuckerrohr-Saft untersucht. Vier Schweine (Kastraten einer Kreuzungen (Yorkshire * Landrasse * Pietrain)) mit einer Anfangsgewicht von 18,7 ± 3,2 kg erhielten unterschiedliche Anteile an silierten New Cocoyam Blätter (ENCL) und frischem Zuckerrohrsaft in zwei aufeinander folgenden Perioden zur Bereitstellung eines unterschiedlichen Rohproteingehaltes von 80 bis 160 g / kg TrM. In der ersten Versuchsperiode wurden 100, 120, 140 und 160 g Rp / kg TS; und in der zweiten Versuchsperiode 90, 110, 130 und 150 t g Rp / kg TM. Der frische Zuckerrohrsaft enthielt 20 bis 21% Gesamtzucker. Die Cocoyam Blätter wurden gehäckselt und unter Zusatz von 10% (bezogen auf Frischmasse) Zuckerrohrsaft siliert (ENCL). Das Blattsilage war von sehr guter Qualität, wie durch Geruch und Farbe und den raschen Rückgang des pH-Wertes (<4) innerhalb von 3 Tagen nach Silierungsbeginn festzustellen war. Die verfütterte Menge an ENCL in der Ration TrM war 0,49, 0,56, 0,67 und 0,76 in der ersten Periode und 0,46, 0,48, 0,57 und 0,67 in der zweiten Periode. Die TrM-Aufnahme war in allen Rationen hoch (zwischen 32 bis 53 g / kg LW) und zeigte eine kurvi-lineare Reaktion zur zunehmenden Aufnahme von ENCL in der Ration, mit einem maximalen Wert von 0,55 ENCL in der TrM der Ration. Mit zunehmendem Anteil der ENCL in der Ration reduzierte sich die Scheinbare Verdaulichkeit der TrM und erhöhte sich die des Rohproteins. Auch die N Retention erhöhte sich mit zunehmendem Anteil der ENCL in der Ration in einer kurvi-linearen Beziehung mit einem maximalen Wert von 0,67 ENCL, das entspricht 130 g Rohprotein je kg TrM / Ration.

In Kapitel 6 wir die Hypothese getestet, das durch die Applikation von Biodigester-Abwässer mit hohem NH_4-N Gehalt kombiniert mit Biochar (Abprodukt aus der Biogas-Verwertung von Zuckerrohr-Bagasse) ein synergistischer Effekt auf das Wachstum von Mais ausgeübt wird. Zwei Experimente zur Überprüfung der Veränderungen der Bodenfruchtbarkeit als eine Funktion des Wachstums von Maispflanzen in den ersten 30-40 Tagen nach Aussaat. In jedem Experiment wurde ein randomisierten Design mit 4 Wiederholungen pro Behandlungen von Bodenproben in einem Ein-Liter-Plastik-Container angewandt. Im ersten Experiment 1wurden 8 Behandlungen in einem 2 * 2 * 2 faktoriellen Design mit den Faktoren (1) mit oder ohne Biochar auf 50g/kg Boden, (2) Mutterboden oder B-Horizont-Boden,(3) und mit oder ohne Biodigester-Abwasser (100 kg N / ha). Im zweiten Experiment wurde Asche aus einem Holzofen statt Biochar verwendet.

Biochar erhöhte das vegetative Wachstum der Maispflanzen auf dem Mutterboden unabhängig vom Fehlen oder Vorhandensein von Biodigester-Abwasser, und im B-Horizont-Boden nur bei gleichzeitiger Applikation von Biodigester-Abwasser. Die Vergabe des Abwassers hatte keinen Einfluss auf das vegetative Mais-Wachstum auf den Mutterböden ohne gleichzeitige Applikation von Biochar. Im Gegensatz dazu erhöhte das Abwasser drastisch das Maiswachstum bei gleichzeitiger Biochar-Düngung des B-Horizont-Bodens, hatte aber keine Wirkung bei Fehlen des Biochar. DasWurzelwachstum wurde in gleicher Weise durch die Behandlungen beeinflusst, außer im Falle des B-Horizont-Bodens, bei dem die Biochar-Düngung ein deutlich erhöhtes Wurzelwachstum erzielte. Der Boden-pH-Wert wurde durch Zugabe von Biochar von 4-4.5 auf 6,0-6,5 erhöht. Holzasche bewirkte eine Erhöhung des Gewichts der Blattmasse und der Mais-Wurzeln aber der relative Anstieg betrug nur 50% jenes bei Biochar-Düngung. Die Versuche belegten synergistische Effekte auf das Pflanzenwachstum in stark ausgewaschen, sauren Böden, wenn Biodigester Abwasser zusammen mit Biochar gedüngt wird.

Kapitel 7 beschreibt Versuche zur Bewertung des Effekts der Wahl von Pflanzmaterial auf dem Biomasse-Ertrag von New Cocoyam. Als Pflanzmaterial wurden Wurzelsprossen von der Basis der Wurzel oder Abschnitte des Stammbereiches genutzt. Es gab 4 Wiederholungen von jeder Behandlung angeordnet in 2 Blöcken an zwei Standorte der Farm, durchgeführt mit einem randomisierten Block-Design mit Pflanzabständen von 70 cm zwischen den Reihen und zwischen den Pflanzen in der Reihe. Versuchsbeginn war am 15. September 2006, die Ernte der Blätter und Stiele begann am 18. Februar 2007 und dauerte im Abstand von 30 Tage bis zum 3. Oktober 2007. Die Erträge an Frischmasse (Blätter und Stiele) waren um 50% höher bei Nutzung von Wurzelsprossen gegenüber Stammmaterial und erreichten einen Frischmasseertrag von 128 Tonnen / ha / Jahr, 14,5 Tonnen TrM und 1,90 Tonnen Rp / ha / Jahr. Die Verwendung von Stammabschnitten als Pflanzmaterial führte zwar zu einer höheren Zahl von Blättern pro Pflanze, aber diese waren viel kleiner als bei jenen aus Wurzelsprossen gezogenen. Mehr Wurzelsprosse wurden von Pflanzen gezogen aus Stammbereichen produziert, aber die allgemeine Entwicklung der Pflanzen war günstiger bei Verwendung von Pflanzmaterial aus Wurzelsprossen.

Die Ergebnisse der kombinierten Silierung von Blättern und Stengeln von New Cocoyam in der werden im Kapitel 8 beschrieben. 40 New Cocoyam Pflanzen der TOSOLY Farm in der Provinz Santander, Kolumbien, wurden komplett geerntet. An zehn Pflanzen erfolgte eine komplette Trennung der Blätter und Stengeln, Gewichtsfeststellung und Vorbereitung für die Analyse des TrM-, N- und Aschegehaltes. Die übrigen 30 Pflanzen wurden in einer Maschine gehäckselt, gemischt in Silierung in 28 luftdichten Kunststoffbehältern von 200 ml Inhalt. Vier Proben wurden zur Analyse am Tag 0 (vor Silierung), 1, 2, 3, 4, 5 und 7 Tage nach Silierung vorgehalten. Die Lagerung der Container erfolgte bei Raumtemperatur in einem geschlossenen Raum. TrM und Rohproteingehalt von frischen Blattstengeln (7,3 und 5,2%) waren viel geringer als in frischen Blättern (17 und 18% in der TrM), aber der Zucker war höher (38 und 20% in der TrM). Der Frischmasse Ertrag von Blattstengeln war doppelt so hoch als jener der Blätter, aber der TrM Ertrag war genau umgekehrt. Der pH-Wert der Frischmasse aus Blattstengeln und Blättern fiel von 5,81 bei Beginn der Silierung auf 4,37 innerhalb von 24 h und 3,98 in 48 h. Der Milchsäuregehalt erreichte nach 7 Tagen Silierung 2,07% in der TrM.

Praktische Erfahrungen bei der kommerziellen Verwendung der Biogasanlage auf dem TOSOLY Hof werden in Kapitel 9 zusammengefasst. Zuckerrohr-Bagasse und einen Mischung aus Pflanzenteilen des Maulbeerbaum (Morus alba) und Tithonia (Mexikanische Sonnenblume) werden für die Beschickung des „Down-Draft Ankur-Vergasers“ genutzt. Die Tests erfolgten unter kommerziellen Bedingungen über einen längeren Zeitraum (90 Tage). Die Bagasse war das Nebenprodukt der Gewinnung von Saft aus Zuckerrohr, das an Schweine verfüttert wurde, die Stengel waren die Rückstände nach der Nutzung von Blättern und (im Falle der Mulberry) Rinde durch Ziegen Der 10KW Vergaser (Ankur WBG10) wurde aus Indien importiert. Der Verbrauch an Rohstoffen war für Bagasse und Stengel ähnlich (4,32 und 4,65 kg TrM / h). Stengel erzielten einen höheren Anteil an Biochar (11,7% der TrM des Ausgangsmaterials) als die Bagasse (8,5%). Das Management des Vergasers war bei Verwendung von Stengeln einfacher, da diese leichter in den Trichter flossen, während die Bagasse eher "Brücke" bildete und häufig aufgeschüttelt werden musste um eine kontinuierliche Gasbildung zu erhalten. Es wurde geschätzt, dass die Bagasse von 1.5ha Zuckerrohr, benötigt für die Fütterung von einem konstanten Bestand von 45 Schweinen (ca. 50 kg TrM täglich), und die Stengeln von 1 ha Futter-Bäume, ausreichend für die Fütterung von 20 Zuchtziegen, eine elektrische Energie Ausbeute von 50 KWh täglich erbringen kann. Der Biochar Rückstand (35% Asche, 65% aus Kohlenstoff) aus der Vergasung von Bagasse und Baumstämmen würde für die Erhaltung von jährlich 0,1 Hektar fruchtbarem Ackerland ausreichen, mit dem Potenzial jährlich bis zu 5,4 Tonnen Kohlendioxid zu sequestrieren

Kapitel 10 untersucht das Verhältnis von Energie-Ertrag zu Energie-EinsatzAufwand (EROEI) auf der TOSOLY Farm mit dem Einsatz von (i) rohfaserhaltigen pflanzlichen Nebenprodukten (Zuckerrohr-Bagasse und Stengel von Futterbäume) als Ausgangsstoffe für eine Biogaserzeugung in einem „gasifier“ und (ii) alle organischen Abfälle mit hohem Feuchteanteil aus der Schweinehaltung und dem Haushalt für einen „Biodigester“ zur Erzeugung von Biogas.

Die Hypothese war, dass die Produktion eines brennbaren Gases aus Biomasse (Vergasung), als Nebenprodukt eines integrierten Betriebsansatzes mit Viehwirtschaft, eine viel höheres EROEI erreicht, und umweltfreundlicher als die Produktion von anderen Biokraftstoffen, insbesondere Produktion von Ethanol aus Mais und anderer "essbarer" Kohlenhydrate ist. Ein dem integrierten Betriebssystem erzeugt Zuckerrohr (1.5ha produziert 120 Tonnen Rohr) die Energie (Zuckerrohrsaft) für einen konstanten Mastschweinebestand von 40 Schweinen, die Futter Bäume (1 ha mit Mulberry und Mexikanische Sonnenblume) liefern das Protein für 20 adulte Ziegen mit Nachzucht, die verbleibende Bagasse (18 Tonnen DM / Jahr) aus dem Zuckerrohr und die Stengel der Futterbäume (6 Tonnen DM / Jahr) sind der Rohstoff für den Vergaser. Der jährliche Ertrag beziffert sich auf 221.760 MJ als „Verarbeitungs-Gas“ und 40.150 MJ als Biogas. Die tägliche Produktion von Strom aus einer Wärme-Gas-Kopplung und Generator ist 54,7 KWh und 8 KWh aus dem Biogas, das insgesamt mehr als das Sechsfache der täglichen Strombedarfs der Farm darstellt. Jährliche indirekte (embedded) Energiekosten wurden auf 33.205 MJ geschätzt von denen 34% aus menschlicher Muskelkraft und 30% aus zugekauftem Tierfutter stammen. Die Erzeugung von 261.910 MJ als brennbares Gas führt zu einem EROEI von 8:1.

Schließlich werden in Kapitel 11 die allgemeinen Ergebnisse der Arbeit in Bezug auf die vorgeschlagene Strategie, zukünftige Anbausysteme auf eine CO_2-Reduzierung auszurichten durch Senkung der Emissionen von Treibhausgasen, eine Stromerzeugung vor Ort aus natürlichen Ressourcen, die maximale Ausnutzung der Sonnenenergie, und die Konfliktvermeidung zwischen der Nutzung der verfügbaren Ressourcen für Nahrungsmittel und Energieerzeugung.

Es wurde festgestellt, dass:

- Die Silage aus Biomaterial (Blätter und Stiele) der Neuen Cocoyam (Xanthosoma Sagitifolium) eine vielversprechendes, eiweißreiche Futter für den Ersatz herkömmlichen Protein-Quellen in der Ernährung für Schweine darstellt,
- Integrierte, kleinbäuerliche Betriebssysteme basierend auf dem Anbau von multifunktionalen Pflanzen und Viehwirtschaft in der Lage sind Lebensmittel, Futtermittel und Brennstoff-Energie ohne Konflikt zwischen diesen Nutzzielen zu erzeugen,
- Die Vergasung von rohfaserreiche Ernterückständen sowohl Elektrizität und bodenverbessernden organischen Dünger (Biochar) erzeugt, das auch zur Sequestrierung von Kohlenstoff aus der Atmosphäre beiträgt. Biogas aus allen flüssigen Abfällen produziert einen gasförmigen Kraftstoff zum Kochen oder zur alternativen Erzeugung von Elektrizität.
- Das System bietet echte Vorteile für die Umwelt (einen negative Kohlenstoff-Fußabdruck) durch Kohlenstoff-Sequestrierung und die Verbesserung der Bodenfruchtbarkeit.

Schlüsselwörter: Biochar, Biodigester, Biomasse, Kohlenstoff-Fußabdruck, Kohlenstoff-bindung, Rinder, Klimawandel, Elektrizität, Energie, EROEI, Rohstoffe, fossile Brennstoffe, Vergasung, die globale Erwärmung, Ziegen, Treibhausgasemissionen, Vieh, Schweine, Fruchtbarkeit des Bodens, nachhaltigen Bewirtschaftungssysteme.

List of abbreviations

ADF Acid detergent fiber

ADG Average daily weight gain

BW Body weight

CF Crude fiber

CF Crude fibre

CP Crude protein

CP Crude protein

CT Condensed tannin

DM Dry matter

DM Dry matter

EROEI Energy returned on energy invested

GDP Gross Domestic Product

GLM General Linear Model

ha Hectare

J Joules

KJ Kilo joules

km Kilometer

LW Live weight

MJ Mega joules

N Nitrogen

NC New Cocoyam

NDF Neutral detergent fibre

OM Organic matter

SD Standard deviation

SEA Southeast Asia

SEM Standard error of mean

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Chapter 1. Introduction: Designing a new farming strategy to respond to the triple crisis of resource depletion, climate change and the failure of the market economic model

Energy as the stimulus to development – and economic recession

The components of the world crises – economic recession, global warming and resource depletion (especially fossil fuels) - presently facing humanity are closely inter-related. The gaseous emissions from the burning of fossil fuels are the major contributor to global warming; the apparently inexhaustible supply of fossil fuels facilitated the exponential growth of the world population during the past century and, more recently, the unsustainable indebtedness in the developed countries, which led to the economic recession of 2008-09.

In the past century, the needs for energy, and indirectly for food, of the expanding world population were provided by cheap oil. The inevitable process of adaptation to increasing cost and declining supplies of oil, will almost certainly change the future life style of the majority of the world's population. On the positive side it will provide greater opportunities for small scale farmers as there will be comparative advantages - economic, social and environmental - for the utilization of biomass for food, feed and fuel production, in a world in the decline phase of the oil age. This is because over 70% of fossil fuel is used for transport. As the supply diminishes and the price increases, transport will be the sector most affected. Most forms of biomass are of low bulk density. Thus, there will also be comparative advantages for decentralization and localization of both production and processing of this resource.

For the future, the only long term alternative to fossil fuel (as exosomatic energy - that is energy not derived from digested food – muscle power) is solar energy, utilized either directly as a source of heat, or indirectly in solar-voltaic panels, as wind, movements of waves and tides, or in biomass produced by photosynthesis. Solar energy will also have to be relied on to produce food, in what must surely have to be small-farm systems in rural areas, to support the largely urbanized population, The green revolution which dramatically increased food supplies during the last 40 years was a "fossil energy " revolution as it was energy in the form of oil and natural gas which facilitated production of fertilizers, especially nitrogen, pesticides and herbicides, and the mechanization and irrigation that permitted multiple cropping.

Another "energy" revolution is possible but it will be based on making greater use of the energy derived daily from the sun. It must produce both energy and food and have an EROEI (Energy Return on Energy Invested) of at least 5 (Hall et al 2008, 2009). It will also need the support of human energy and increased numbers of people working in rural areas.

There are few difficult decisions about producing food by photosynthesis. By contrast, the ideas proposed for redirecting energy from the sun into potential energy to replace that of fossil fuels are many. Rapier (2009) describes many of these proposals as *Renewable Fuel Pretenders* arguing that their proponents believe they have a solution but that it will never develop into a feasible technology because the proponents "have no experience at scaling up technologies". In this category he lists cellulosic ethanol, hydrogen and diesel oil from algae.

It is surprising that gasification of biomass, as a means of producing a combustible gas, has received so little attention – perhaps because it is not a new technology. It is one of the purposes of this thesis to demonstrate that it holds real prospects of being applicable at the small, dispersed farm level, provided it is developed as a component of a mixed, integrated farming system.

Gasification is a process for deriving a combustible gas by burning fibrous biomass in a restricted current of air. The process is a combination of partial oxidation of the biomass with the production of carbon which at a high temperature (600-800 °C) acts as a reducing agent to break down water and carbon dioxide (from the air) to hydrogen and carbon monoxide, both of which are combustible gases.

The advantages of gasification are that: the feedstock is the fibrous parts of plants which are not viable sources of food or feed; the energy used to drive the process is derived from the combustion of the feedstock; there is minimal input of fossil fuel (mainly for the construction of the gasifier and associated machinery); and the process can be de-centralized as units can be constructed with capacities between 4 and 500KW.

Food, feed and energy from biomass

Several writers (eg; Brown 2007; Falvey 2008) have challenged the morality of converting food into liquid fuel, in a world where one third of the population is already mall-nourished with certain prospects that this proportion will increase as the world population marches on to the 8 to 9 billion predicted before the mid-point of this century. Second generation ethanol from cellulosic biomass is also not the answer, as apart from the doubtful economics of the process, the major proposed feedstocks – Switch grass and Miscanthus – provide no food component.

As indicated earlier, this conflict can be avoided by using gasification to produce the fuel energy, as the feedstock can be the cellulosic component of the plant, leaving the more digestible protein and carbohydrate components as the source of food/feed. The most useful end products of gasification are electricity and biochar, thus electrification of most road transport systems is a necessary corollary. Utilization of biochar will be facilitated by locating the gasification process within the farm producing the biomass.

Sugar cane, protein-rich forages and pigs

The choice of sugar cane as the pivotal crop in the farming system is justified by it's high yield and efficient use of solar energy, and the ease of separating the 100% digestible sugar cane juice from the structural fibre (bagassse). Because the juice contains no fibre, it is the perfect medium for facilitating the incorporation in diets for pigs of protein-rich vegetative sources such as the edible leaves of trees, shrubs and vegetables, the levels of which in cereal-based diets are constrained by their moderately high levels of fibre. Research has been done with several protein-rich forages, including the leaves of cassava and mulberry, the vines of sweet potato, the leaves and stems of water spinach and more recently the leaves and stems of Taro, Cocoyam and New Cocoyam (Preston 2006). Chhay Ty et al (2009) recently reviewed the research done with these different forages and came to the conclusion that the Colocacia, Alocacia and Xanthosoma members of the Araceae family offered the greatest potential as vegetative protein sources in pig diets because of their high yield, ease of cultivation (many species grow wild in ponds and in the forests (Peng Buntha et al 2008; Ngo Huu Toan and Preston 2007), ease of conservation by ensiling, and the apparent relatively high energy value of the stems complementing the protein in the leaves.

The choice of pigs as the main live stock component in an integrated farming system is justified by several factors: ease of marketing the meat, low investment (compared with cattle), and the fact that pig excreta is the preferred feedstock in anaerobic biodigesters.

http://www.fao.org/WAICENT/FAOINFO/AGRICULT/AGA/AGAP/FRG/recycle/default.htm.

For the above reasons, studies on the nutritive value in pig diets of New Cocoyam (*Xanthosoma sagittifolium*) were chosen as the objectives of the research in chapters 3, 4 and 5; while in Chapter 6, attention was given to the agronomic aspects of cultivating New Cocoyam.

Sugar cane, forage trees and goats

The advantages offered by sugar cane as a combined source of feed for pigs and gasifier feedstock have already been discussed. A similar synergism applies to the use of forage trees as the protein source for goats. The browsing habit of this species facilitates the separation of the leaves, which become the protein component of the diet, while the residual stems are easily processed as feedstock for the gasifier.

In the TOSOLY farming system, the chosen trees species are Mulberry (*Morus alba*) and Tithonia (*Tithonia diversifolia*). Mulberry leaves have been extensively studied as a protein source for ruminants, mainly goats (Yao et al 2000; Theng Kouch et al 2003; Nguyen Xuan Ba et al 2005; Pathoummalangsy Khamparn and Preston 2008; Khamphoume Souksamlane et al 2009). The conclusion of Khamphoume Souksamlane et al (2009) was that Mulberry leaves almost certainly were rich in "bypass" protein in view of the marked increases they induced in the growth rate of goats.

The multi-purpose role of sugar cane is apparent in the fact that for pig feeding and gasification, only the stalk is used. The growing point and leaves are thus available as a potential energy-feed resource for ruminants.

Integrated farming systems

In a recent paper, on the "Post Carbon Institute" web site, Heinberg and Bomford (2009) stated that

"The only way to avert a food crisis resulting from oil and natural gas price hikes and supply disruptions while also reversing agriculture's contribution to climate change is to proactively and methodically remove fossil fuels from the food system". Their proposals in relation to farming systems were that:

> "Farmers should move toward regenerative fertility systems that build humus and sequester carbon in soils, thus contributing to solving climate change rather than exacerbating it. More of the renewable energy that will power society can and must be generated on farms. Wind and biomass production, in particular, can provide farmers with added income while also powering farm operations".

In the same report they referred to papers indicating that, compared with large farms, "smaller farms have greater biodiversity (Hole eta l 2005), more emphasis on soil-building (D'Souza and Ikerd 1996) and greater land-use efficiency (Rossett 1999)".

In a review of the investment opportunities in agriculture to increase food production in a resource-depleted world (Kahn and Zaks 2009), the point was made that "Alternative approaches are being researched and tested in development such as the reemergence of small, self-sufficient organic farms, characterized as local, multi-crop, energy and water efficient, low-carbon, socially just, and self-sustaining".

The hypothesis underlying the research

This thesis is a contribution to the strategy that should underpin all future farming systems: namely the need to "de-carbonize" the system, by reducing emissions of greenhouse gases, generating electricity locally from natural resources, making maximum use of solar energy and ensuring there is no conflict between use of available resources for both food and fuel production.

Research objectives

The research described in this thesis relates to the following components of the farming system:

- Biomass yield of New Cocoyam grown for forage
- Ensiling the leaves and petioles of New Cocoyam
- Nutritive value for pigs of fresh leaves of New Cocoyam
- Production parameters of the down-draft gasifier using sugar cane bagasse as feedstock
- Use of the biochar residue from gasified bagasse as soil conditioner

It will be shown that:

- instead of conflict in the use of biomass for food and fuel, there can be synergism,
- and that, instead of contributing to climate change, the farm can have a negative carbon footprint

The caveat, however, is that the farming system is small scale, with close integration among crops, trees, animals and people, with recycling of all wastes.

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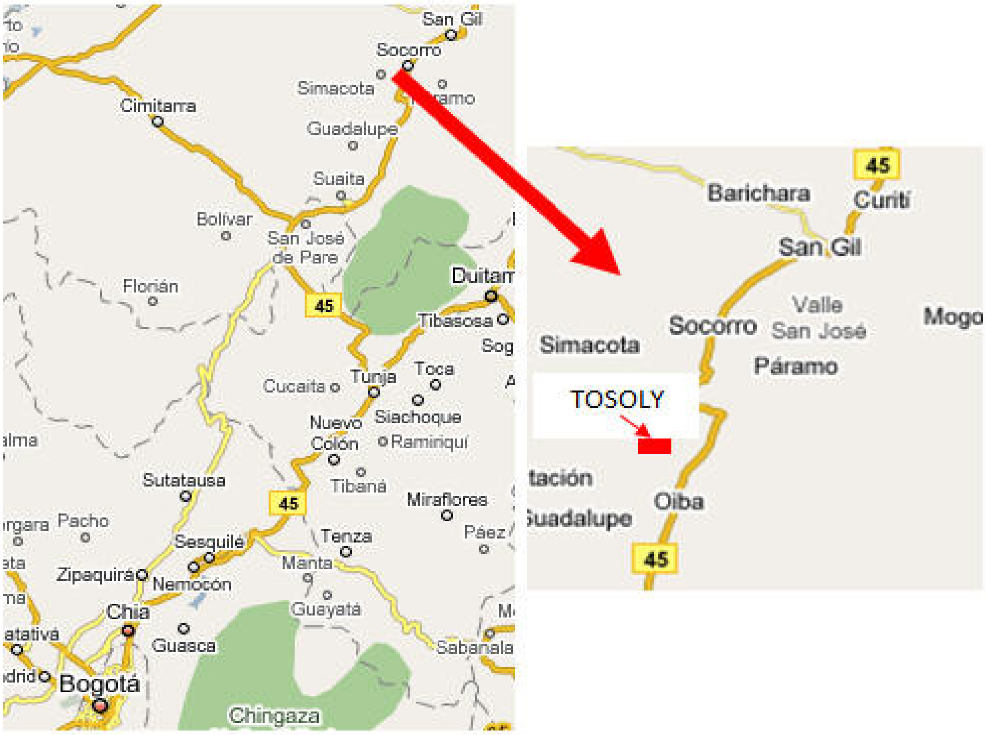
Chapter 2. Location of the research; the TOSOLY farm in Santander, Colombia

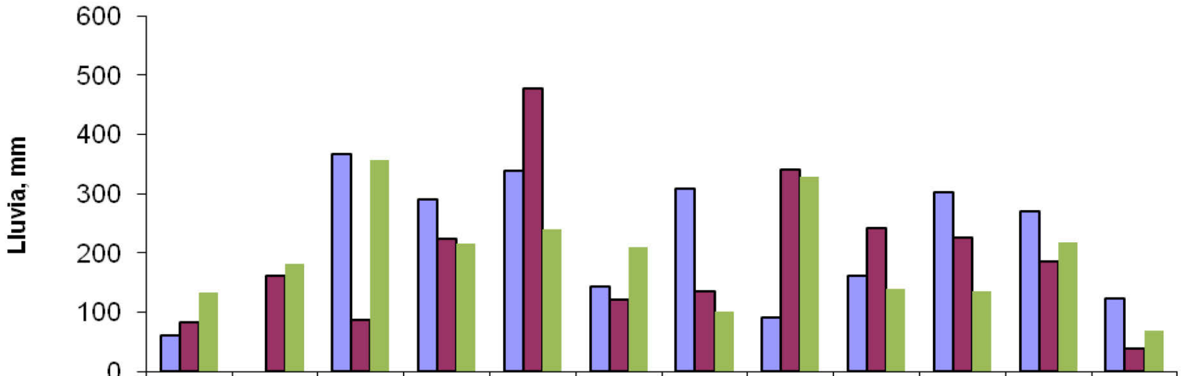
Introduction

The research has been carried out on a farm in the Colombia foothills, in the Department "Santander Sur", 20 km from the town of Socorro (Map 1).



Map 1. Location of the TOSOLY farm

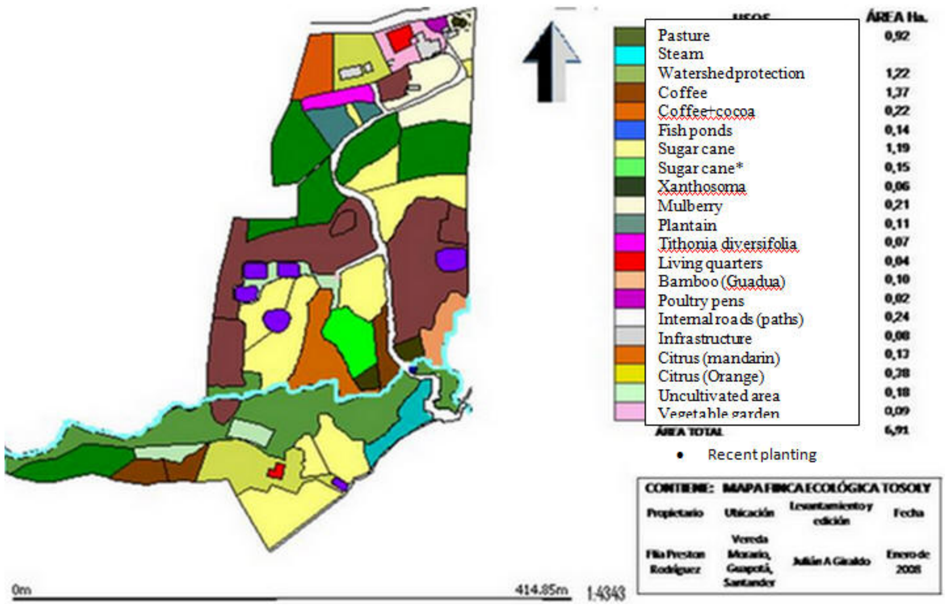
The region is characterized by relatively uniform rainfall ((Figure 1) and soils that are acidic (pH 4.0-4.50).



	Enero	Febr	Marz	Abril	Mayo	Junio	Julio	Agos	Sept	Oct	Nov	Dic
2007	60	0	366	290	338	144	309	91	162	302	270	123
2008	83	161	88	225	477	122	135	340	243	226	187	38
2009	134	182	357	216	239	210	102	329	139	135	217	70

Figure 1. Monthly rainfall in TOSOLY farm during 2007-2009

The farm is situated at 1500 masl and occupies an area of 7ha on a hillside with overall slope of 20% (difference in height of 60m over a distance of 350 m). Traditionally the soils in the region have been, and continue to be, exploited for shade "Arabica" coffee and small scale production of "Panela" from sugar cane. In order to promote biodiversity, the crops on the farm are replicated in different areas (Map 2). The principal crop is sugar cane (Photo 1), presently occupying 1.34 ha but projected to increase to 2 ha as the pasture areas are gradually displaced with more productive crops.



Map 2. Distribution of the cropping areas in TOSOLY farm

Tree crops include coffee, cocoa, and forage trees (chiefly mulberry [*Morus alba*] (Photo 2], and "Boton de oro" [*Tithonia diversifolia*] (Photo 3), forage plants (New Cocoyam [*Xanthosoma Sagittifolium*] (Photo 4) and Water spinach [*Ipomoea aquatic*] (Photo 5) and trees for timber and fuel, including a grove of 'Guadua"(*Guadua angustifolia*) (Photos 6 and 7), and for shading the coffee (Photo 8).

Photo 1. Sugar cane is distributed in different areas of the farm always in close proximity to trees

Photo 2. Mulberry (*Morus alba)* is the major protein source for goats, cattle and rabbits

Photo 3. "Boton de oro" (*Tithonia diversifolia)* has excellent agronomic properties and is fed to the goats along with the mulberry foliage

Photo 4. New Cocoyam (*Xanthosoma saggitifolium*) is the preferred protein source for the pigs

Photo 5. Water spinach (*Ipomoea aquatica)* a high protein vegetable for people and animals. Needs neutral soils but is now grown in the farm after soil amendment with Biochar (Chapter 6).

Photo 6. "Guadua *(Guadua angustifolia)* finds major uses on the farm for construction (Photo 7)

Photo 7. " Guadua" provides the support structure of the plastic canopy for drying the coffee beans, the bagasse and the stems of mulberry and Tithonia

Photo 8. Guamo *(Inga hayesii* Benth) is the traditional shade tree for coffee

The livestock and fuel components are chosen for their capacity to utilize the crops and byproducts produced on the farm. Sugar cane stalk is fractionated into juice and residual bagasse. The tops including the growing point and some whole stalk are the basal diet for dual purpose cattle and goats. The juice is the energy feed for pigs (Photo 9) and the source of "sweetener" for cooking for the farm family.

Photo 9. Sugar cane juice is the basal diet for the pigs

The bagasse (Photo 10) is the fuel source for a gasifier (Photo 11) that provides combustible gas for an internal combustion engine linked to an electric generator.

Photo 10. The bagasse is sun-dried and separated into fine (on the left) and coarse particles (on the right); the former for the gasifier and the latter as litter for the cattle and goats

The goats are the means of fractionating the forage trees (Photo 12), consuming the leaves, fine stems and bark as sources of protein, with the residual stems being another source of fuel in the gasifier.

Photo 11 The down-draft gasifier for converting fibrous biomass to electricity

Photo 12. Goats are very efficient in fractionating the mulberry and the Tithonia, consuming the leaves and leaving the stems for the gasifier

The pig unit has capacity for 40 growing-fattening pigs and 5 sows (Photo13a,b).

Photo 13a,b. New housing for pregnant and lactating sows uses local materials and a construction technique (" el muro tendenoso") that reduces cement needs by more than 50% and eliminates need for bricks. The amount of "embedded" fossil fuel energy is much reduced by this system.

The goat unit (Photo 14) has 10 breeding does and 2 bucks. There are 3 pens for 2 crossbred cows and progeny (Photo 15), kept for triple purpose production of milk, meat and manure.

Photo 14. The coarse bagasse not suitable for the gasifier is an excellent bed for the goats. Mulberry and Tithonia are suspended in racks, a technique that has been shown to stimulate feed intake (Theng Kouch et al 2003)

Photo 15. Multi-purpose cows produce, milk, meat and manure

Hens (n=40) and ducks (n=6) are raised in semi-scavenging systems (Photos 16 and 17) for eggs and meat.

Photo 16. Scavenging hens help to control the weeds under the forage trees

Photo 17. Duckweed (*Lemna minor*) is highly appreciated by the ducks in as semi-scavenging system

Rabbit production is a new venture on the farm, applying the principles of 100% forage diets developed in Cambodia, Laos and Vietnam
(http://www.mekarn.org/prorab/content.htm)
(Photo 18).

Photo 18. Rabbits are fed exclusively on forages produced on the farm

A horse serves to transport sugar cane and forages (Photos 19 and 20).

Photos 19 and 20. Horses do not need fossil fuel

All high moisture wastes are recycled through plug-flow, tubular plastic (Polyethylene) biodigesters. Pig and human excreta are the feedstock for four biodigesters (Photo 21). Waste water from coffee pulping, washing of dishes and clothes go to a fifth biodigester (Photo 22).

Photo 21: Three biodigesters receive washings from the pig pens and from the family toilets

Photo 22: Waste water from the kitchen, the clothes washer and the machine for pulping fresh coffee beans is directed to this biodigester

Effluents from all biodigesters are combined (Photo 23) and recycled to the crops as fertilizer.

Photo 23. Effluents from all the biodigesters are recycled to the crops and forages as fertilizer

The pens for the goats and cattle have clay floors covered with a layer of bagasse to absorb the excreta (Photos 14 and 15). Periodically this manure is returned to the crops as fertilizer and as a source of organic matter (Photo 24).

Photo 24. Manure from the cattle and goats is a major source of fertilizer and organic matter for recycling to the crops

The features and links of the farming system are shown in Figure 2.

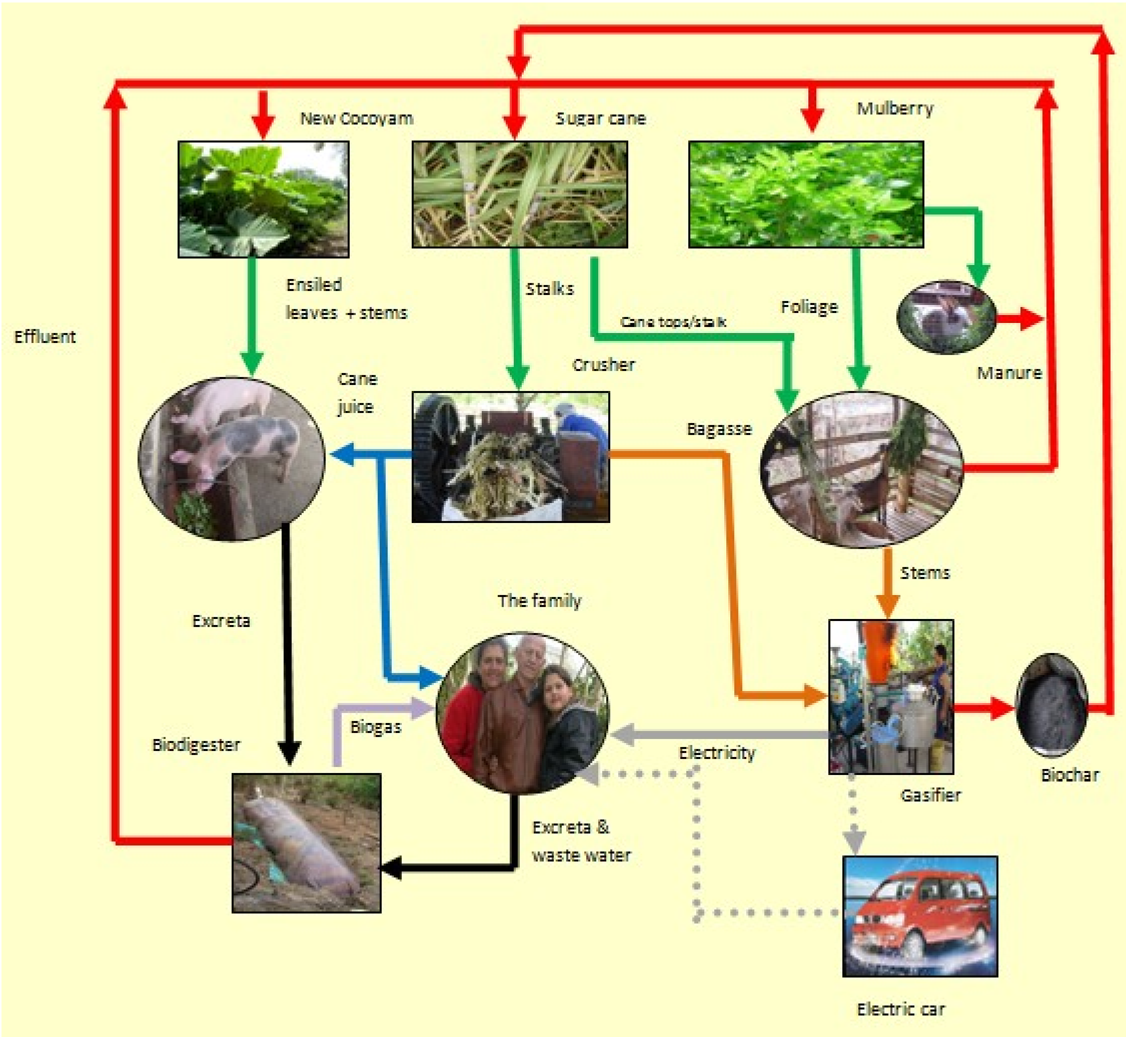


Figure 2. The features and links of the farming system in TOSOLY

Chapter 3. New Cocoyam (*Xanthosoma sagittifolium*) leaves as partial replacement for soya bean meal in sugar cane juice diets for growing pigs

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Abstract

Twelve pigs in 4 pens (3 animals in each) were used to compare two treatments in a completely random design with 2 repetitions. The treatments were soybean meal at 500 g/animal/day (control) and fresh leaves of New Cocoyam (4 kg/animal/day and 250 g/animal/day of soybean meal). The rest of the diet was sugar cane juice and a mineral supplement. The trial lasted 56 days during the growth phase from 25 to 56 kg live weight.

There were no differences between treatments for the parameters: DM intake, weight gain and feed conversion, the values of which were within the range normally observed for this type of diet.

The results are preliminary but they indicate the potential of fresh New Cocoyam leaves to replace up to half the soybean protein in diets based on sugar cane juice for growing pigs.

Key words: Growth, local resources, new cocoyam, pigs, protein, soybean, sugar cane juice

Hojas de Bore (*Xanthosoma sagittifolium*) como reemplazo parcial de la proteína en dietas para cerdos basadas en jugo de caña

Resumen

Se usaron 12 cerdos alojados en 4 corrales (3 animales en cada uno) para comparar dos tratamientos en un diseño completemente al azar con 2 repeticiones. Los tratamientos fueron torta de soya a nivel de 500 g/animal/día (testigo) y hoja fresca de Bore (4 kg/animal/día y 250 g/animal/día de torta de soya). El resto de la dieta fue jugo de caña de azúcar y un suplemento mineral. El ensayo duró 56 días sobre la fase de levante desde 25 a 56 kg de peso vivo de los cerdos.

No hubo diferencias entre tratamientos para los parametros de consumo total de MS, ganacia de peso y conversión alimenticia, siendo los valores dentro del rango normalente observados en este tipo de dieta.

Los resultados son preliminares pero indican el potencial de las hojas frescas del Bore para reemplazar hasta la mitad de la torta de soya en dietas basadas en jugo de caña para cerdos en crecimiento.

Palabras claves: Bore, cerdos, comportamiento productivo, etapa de levante, jugo de caña, recursos locales, torta de soya

Introduction

In industrialized countries to optimize pig production means to maximize weight gain with diets formulated on a least cost basis. It is generally assumed that improvments in economic performance will be associated with increased rate of animal productivity. However, in most developing countries this strategy is not appropriate because of the high costs of conventional feed ingredients (maize, soybean meal and fish meal), many of which are imported. This creates problems of balance of payments at national level and dependence on credit at the level of the producer. Attempts to produce the ingredients locally (principally maize and and soya beans) are constrained by high prices of machinery, seeds and agrochemicals, all of which usually have a content of imported components. Moreover, in most developing countries, cereal grains such as maize are utilized primarily in the human diet, which elevates the price and makes it difficult to include them in feed for animals. Another issue is that the climate and soils in tropical latitudes are not favorable for maize cultivation, which results in lower yields and higher costs of cultivation. The final point is that pig production is often not considered as a component of the farming system, but rather as a specialized activity producing only meat. . By contrast, in an integrated system, pigs are multipurpose animals producing fertilizer and energy as well as meat.

The implication of the above analysis is that in tropical latitudes there is a need to develop feeding systems which make maximum use of plant species which are adapted to, and exploit, local ecosystems. The use of sugar cane as a replacement for cereals as the energy component of the diet, for both ruminant and monogastric live stock (Preston and Leng 1987), is an example of such a strategy. However, the application of this feeding system to pig production, initiated in Colombia in the '80s (Sarria et al 1990), was constrained by the dependence on soybean meal (usually imported) as the source of protein.

The idea of using protein-rich foliages as a replacement for soya and fish meals in practical pig diets was first applied in Vietnam with the use of fresh duck weed (*Lemna* spp) as the only protein source in pig diets in which sugar cane juice provided the energy (Rodríguez and Preston 1996). The leaves from the cassava plant (*Manihot esculenta*), initially in sun-dried or ensiled form, were shown to have potential to replace up to 30% of the protein in diets for growing pigs based on cassava root meal (Bui Huy Nhu Phu et al 1996). Fresh foliage of water spinach (*Ipomoea aquatica)* gave good results as the only source of supplementary protein in diets for young growing pigs in which the energy was from broken rice (Ly 2001), and was shown to have a synergistic effect on pig growth rates when mixed with fresh cassava leaves in broken rice diets (Chhay Ty and Preston 2005). Sweet potato leaves were used successfully as a protein source in pig diets in Vietnam (Le Van An et al 2003) as were the leaves of the mulberry tree (*Morus alba*) (Phiny et al 2003).

Two factors facilitate the use of leaves from tropical trees and shrubs as protein sources in pig diets. The first was the demonstration that the conventional protein requirements for pigs (eg: NRC 1988) could be reduced by up to 40% (Speer 1990), when the protein in the diet had the required balance of essential and non-essential amino acids, subsequently referred to as the "ideal protein" (Wang and Fuller 1989). Leaf proteins, being composed mostly of enzymes necessary for growth of plant tissue, have an amino acid balance that resembles the "ideal" protein. Thus diets in which the protein comes exclusively (basal diet of sugar cane juice) or mainly (cassava roots and broken rice) from leaves of plants can be compounded with lower protein levels (up to 40% less) than when cereal grains such as maize or sorghum are the source of energy, as more than 50% of the protein in such diets is from the cereal component with an imbalanced array of amino acids (Speer 1990). The second factor relates to the capacity of the pig to consume and digest fibre. Leaves from trees, shrubs and crop plants are relatively high in fibre hence the advantages of using energy sources, which are low in fibre (sugar cane juice, cassava roots, sweet potato tubers, banana fruit and broken rice all fall into this category). Use of these feeds as energy sources creates "space" in the diet for protein supplements relatively high in fibre as is the case of leaves from trees, shrubs and crop plants.

The New Cocoyam (*Xanthosoma sagittifolium*) is widely distributed in tropical latitudes. The leaves and roots of some of the wild varieties are reported to contain oxalate crystals which cause itchiness in the mouth. The cultivated variety is said not to have this characteristic (Göhl 1971). In Hue province in Vietnam the leaves and roots are used by farmers as animal feed (Le Duc Ngoan 2006, personal communication). In the farm where the present study was undertaken (6° 18" N, 73° 32" W, 1500 msl), the New Cocoyam produces a high yield of above-ground biomass, growing naturally in moist areas and tolerating partial shade (Lylian Rodríguez, unpublished observations). Like the plantain and banana trees *(Musa* spp)*,* new leaves are produced at 2-3 week intervals, eventually dying and falling to the ground after some 15 days.

In Colombia the root has been used traditionally to feed chickens and pigs and it is usually chopped and cooked. Some farmers use the leaves to feed chickens and fish. In the mountainous areas in Colombia the New Cocoyam is part of the farming systems and since 2003 it has been used in the TOSOLY ecological farm as part of the pig diet combined with other leaves such as cassava (*Manihot esculenta* Cranz), aro (*Trichanthera gigantea),* water spinach (*Ipomoea aquatica*) and whole bean foliage. The proportion of leaves in the diet was dictated mainly according to the availability of the leaves. In this period of observations, the New Cocoyam was found to be one of the most promising forages for its re-growth capacity, high yield and palatability. In the beginning, the petioles as well as the leaves were fed but since 2005 the strategy was changed with the leaves being used for the growing pigs, while the petioles were considered to be more appropriate for feeding to pregnant sows, which need lower levels of protein in the diet as well being able to deal with bulky feeds.

Sugar cane and New Cocoyam have a high potential for forming the basis of pig production within an integrated farming system in tropical latitudes. The juice from sugar cane, which contains neither fibre nor protein, is easily expressed from the stalks and is an ideal complement for protein-rich forages such as New Cocoyam. Both are perennial plants with high biomass yield and are therefore good "sinks" for carbon. New Cocoyam grows well in association with tree crops such as cocoa, coffee and citrus, which adds another dimension to these farming systems.

The present study is the first in a series aimed to document the value of the leaves of New Cocoyam as a protein source in pig diets based on sugar cane juice.

Material and methods

Location

The study was carried out in the "Finca Ecológica", TOSOLY, Morario, Guapota, Department of South Santander, Colombia (6° 18" N, 73° 32" W, 1500 msl) between July and November 2005. Air temperature ranges between 19 and 28°C in the day, falling to around 12°C during the night. Rainfall is between 2700 and 3000 mm/year.

Treatments and design

The two treatments were degree of substitution of soybean meal by fresh leaves of New Cocoyam as sole protein sources in diets of sugar cane juice for growing pigs:

- SB: Soybean meal 500 g/pig/day
- GT: Soybean meal 250 g/pig/day supplemented with fresh leaves of New Cocoyamat levels of 4 kg/pig/day.

There were two repetitions of each treatment, with groups of 3 animals allocated to each of 4 pens according to a completely randomized design.

Animals

The pigs were crossbreed (Yorkshie*Landrace) and at the start were 75 days old with an average weight of 24.8±1.26 kg. They had been vaccinated previously against swine fever and were treated with Estrongol (Diethylcarbamazine citrate; VICAR Co) to eliminate internal parasites. There was a period of adaptation of 1 week before beginning the recording of data which was terminated after a total trial period of 56 days.

Feeds and management

Leaves plus petioles (Figure 1) of New Cocoyam were harvested daily from plants of different ages located in the farm or in the grounds of neighbors (Photo 1). The leaves were separated from the petioles and passed through a mechanical forage chopper before being fed immediately to the pigs in treatment GT. The soybean meal was purchased from a commercial supplier in the nearby town of Socorro. Stalks of sugar cane, grown on the farm or purchased from neighbours, was passed once through a 3-roll mill (Photo2) to separate the juice from the residual fibre (bagasse). The juice was fed immediately after extraction in quantities that the pigs were able to consume completely before the next meal. A mineral mixture (salt 33.3, rock phosphate 33.3 and magnesium limestone 33.3, parts by weight) was fed daily in quantities equivalent to 1% of the daily DM intake.

Photo 1: Leaves of New Cocoyam ready for chopping

Photo 2: The chopped New Cocoyam leaves were readily consumed

The supply of protein was set at a fixed level of 200 g/day, based on the extensive experience with diets of cane juice fot growing-fattening pigs, carried out by commercial farmers in the Department of Valle, Colombia during the decade of the '90s (Sarria et al 1990). The soybean meal (SB) and the mixture of soybean meal and chopped New Cocoyam leaves (NC) were given in two meals daily, at 07.00 and 13.00 hours. The cane juice was given at 10.00 and 16.00 hours. The objective of this feeding strategy was to ensure the total consumption of the protean component before offering the cane juice due to the high palatability of this ingredient. The quantities of cane juice that were fed were calculated on the basis of an expected total DM intake of 50 g per 1 kg of live weight of the pigs. As the offer level of the protein ingredients was fixed, this resulted in the cane juice supplying from 50 rising to 80% of the total diet DM during the course of the 56 days of trial.

The pig pens, which were washed every second day, were connected to a 5 m^3 plastic biodigester, which produced biogas for cooking and nutrient-rich effluent to fertilize the crops.

Measurements

The pigs were weighed at the beginning of the trial, in the morning before offering the new feed, and subsequently at 7-day intervals for a total of 8 weights in 56 days. The daily gain in live weight was determined from the linear regression of live weight (Y) on days in the trial (X). Feed offered was recorded daily. There were no refusals of any of the diet ingredients. The content of total sugars ("Brix" value) in the cane juice (assumed to be equivalent to the DM content) was measured daily with a hand refractometer. Samples of the taro leaves were taken at intervals during the trial for determination of DM by micro-wave radiation (Undersander et al 1993) and nitrogen according to the "Kjeldahl" procedure (AOAC 1990). Protein was calculated as N*6.25.

Statistical analysis

The data (feed intake, weight gain and feed conversion) were analyzed according to the General Linear Model option of the ANOVA of the Minitab (2000) software. The sources of variation were: treatments and error.

Results and discussion

The fresh weight of the New Cocoyam foliage (leaf plus petiole) ranged from 450 to 650 g, of which about 40% corresponded to the leaf component. The average value of DM in fresh leaf was 110 g/kg. This value and those for crude protein and crude fibre (Table 1) are similar to those (160, 220 and 100 g/kg DM, respectively) reported in Tropical Feeds (Göhl 1971) for New Cocoyam leaves in Trinidad. The levels of crude fibre and NDF in the leaves (Table 1) are lower than for most leaves presently being studied as protein supplements for pigs. High values for calcium (1.78%) and low values for phosphorus (0.64%) were also reported by Göhl (1971) and emphasize the need to provide additional sources of phosphorus when the leaves are to be fed to pigs.

Table 1: Composition of the leaves of the New Cocoyam (g/kg DM)

	CP	Ash	NDF	ADF	CF	Ca	P	K	Mg
Taro	248	133	255	198	142	17.7	2	32.3	2.2

The balance of the first-limiting essential amino acids (Table 2) in the New Cocoyam leaves is much closer to the "ideal" protein than in typical samples of soybean meal (Figure 1).

Table 2: Composition (g/kg crude protein) of the leaves of the New Cocoyam compared with soybean meal

	Lysine	Methionine	Cystine	Met+Cys	Threonine
New Cocoyam	46.0	27.1	12.2	26.9	49.5
Soybean	63.2			28.3	38.9

Data for taro from samples in the present experiment; Data for soybean from analyses of 900 samples in USA (Martin M 1999)

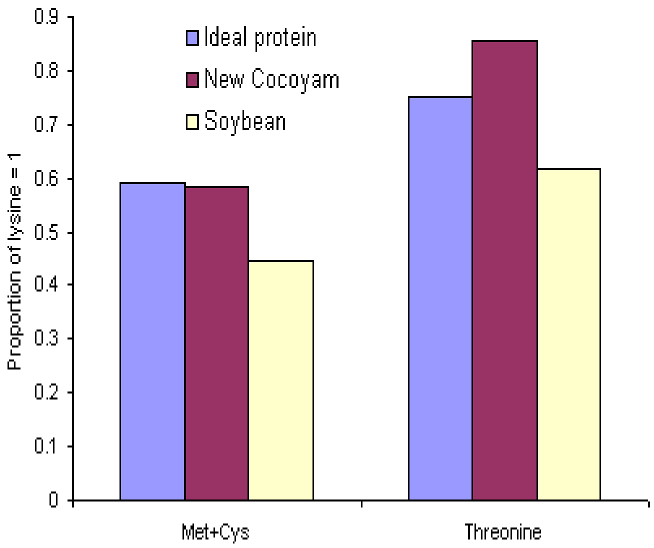

Figure 1: Levels of methionine+cystine and threonine as proportion of lysine = 1.00
Data for New Cocoyam from samples in the present experiment; Ideal protein from Wang and Fuller (1989)
Data for soybean from analyses of 900 samples in USA (Martin M 1999)

The "Brix" (approximates to the content of total sugars) of the sugar cane juice ranged from 15 to 20.5 during the trial, with an average value of 17.7 (Figure 2).

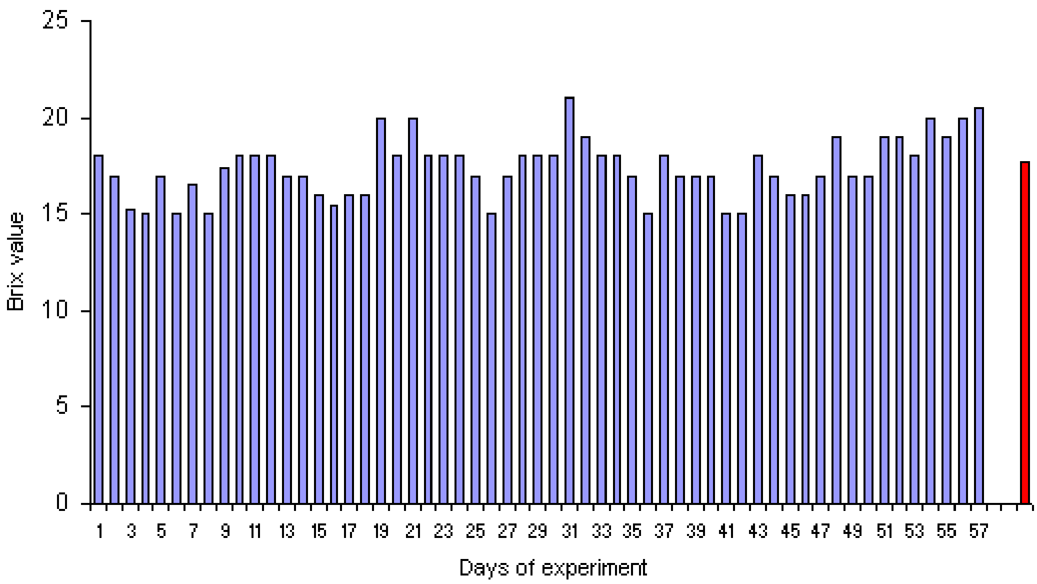

Figure 2: Brix of the cane juice (approximates to total sugars) during the experiment. The red column is the overall mean.

There were no differences between treatments in any of the recorded parameters (Table 3). The curves of growth (Figure 3) show that the gains in weight were uniform throughout the trial and parallel for the two treatments.

Table 3: Mean values for feed intake, live weight change and feed conversion for pigs fed sugar cane juice supplemented with 500 g/d of soybean meal (SB) or 250 g/d soybean meal and 4 kg/d of fresh leaves of New Cocoyam **(NC)**

	NC	SB	SEM	Prob.
Live weight, kg				
Initial	22.4	25.9	1.8	
Final	56.4	59.8	3.8	
Daily gain	0.524	0.519	0.079	0.97
Intake, kg/d				
Cane juice	6.86	8.22	0.60	0.19
Fresh cocoyam leaves	3.78	0.00		
Soybean meal	0.250	0.472	0.013	
Total DM	1.85	1.88	0.180	0.86
Crude proteín	0.195	0.204		
DM conversion	3.67	3.76	0.222	0.81

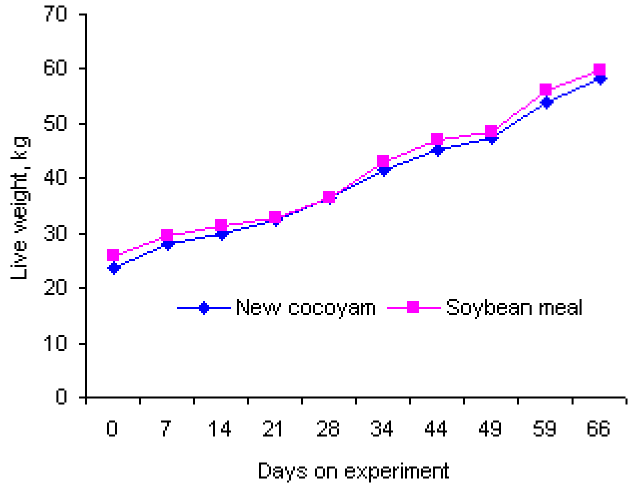

Figure 3: Growth curves of pigs fed sugar cane juice and either 500 g/day soybean meal or 3.8 kg/day New Cocoyam leaves and 250 g/day soybean meal

The New Cocoyam leaves contributed 50% of the protein in the NC treatment (Figure 3). There were no refusals of the New Cocoyam leaves which is a measure of their high palatability. The live weight gains of 524 and 519 g/day for the diets NC and SB were slightly lower than the average of 588 g/day recorded in 8 trials with growing pigs carried out in the Department "Valle" of Colombia (Sarria et al 1990), using comparable diets to the control (fresh cane juice ad libitum and 500 g/animal/day of soybean meal). The feed conversion data (3.67 and 3.76 kg DM/kg live weight gain) were also similar to those (3.4 and 3.8) reported by Sarria et al (1990). The intakes of protein of 195 and 204 g/animal/day in diets "NC" and "SB" are equivalent to concentrations of 10.5 and 10.9% in the DM of the diet, and approximate to the the levels recommended for this system (Preston 1995) of 200 g/day of protein and 10% crude protein in the diet DM .

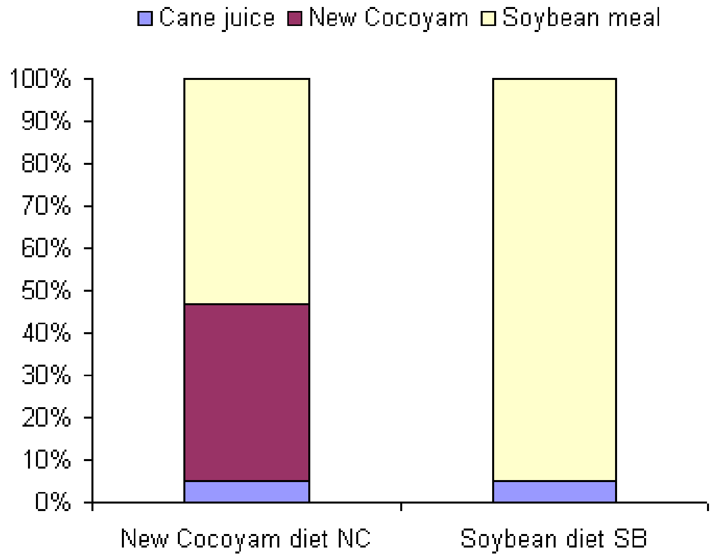

Figure 4: Proportions of dietary protein derived from soybean, New Cocoyam and sugar cane juice in the two experimental diets

A preliminary report on the use of *Alocasia macrorrhiza* foliage (a similar plant to New Cocoyam) for pigs (Basta 2002) indicated that it could replace 40% of the conventional "concentrate" diet of pregnant sows. However, the *Alocasia macrorrhiza* foliage was the leaf plus petiole which it is estimated would have an average of 15% crude protein in DM. Assuming the commercial concentrates also contained 15% crude protein in DM, then the *Alocasia macrorrhiza* foliage would be supplying 40% of the total protein offered, which can be compared with the 50% of the dietary protein supplied by the New Cocoyam leaves in the present study.

Conclusions

- The results of this preliminary study indicate that the growth performance of pigs is not affected when 3 - 4 kg/day of the fresh leaves of New Cocoyam are fed as replacement of 50% of the normal allowance of soybean meal in a diet based on fresh sugar cane juice.

Acknowledgements

The participation of Mr Deibys J Lopez in this study was made possible through a scholarship granted by the Foundation of San Martin University, Baranquilla. The support of the Rector, Dr Jose Alvear, and of the Dean of the Faculty of Veterinary Medicine and Animal Husbandry, MVZ Juan Becerra, is gratefully acknowledged. We are grateful to Professor Brian Ogle, who arranged for the proximate and amino acid analyses of the New Cocoyam leaves, which were done in the laboratories of the Swedish University of Agricultural Sciences, Uppsala, and in a commercial laboratory in Sweden, respectively. The infrastructure and inputs used in the research were provided by the UTA Foundation.

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Chapter 4. Nutritive value for pigs of New Cocoyam (*Xanthosoma sagittifolium*); digestibility and nitrogen balance with different proportions of fresh leaves and soybean meal in a basal diet of sugar cane juice

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Abstract

The four treatments applied to 4 growing pigs in a 4*4 Latin square arrangement were levels of fresh leaves of New Cocoyam (*Xanthosoma sagittifolium*) (NC) equivalent to 0, 30, 60 and 100% substitution of the protein from soybean meal in a basal diet of fresh sugar cane juice. The pigs were crossbred castrated males (Yorkshire*Landrace*Pietran) with initial weight of 13.4±0.54 kg. They were maintained in metabolism cages made from wood and bamboo. Experimental periods were of 14 days with collection of faeces and urine during the last 5 days of each period.

There were significant effects of N intake on DM intake, urine N excretion, and N retention. Adjusting the data for these variables by covariance for differences in N intake changed markedly the treatment effects on DM intake and N retention. After adjustment, DM intake was highest for NC100 and lowest for NC0, while N retention was similar on all diets. N retention as a proportion of the N digested was higher on the diets containing Cocoyam leaves. Apparent OM digestibility declined from 920 to 808 and that of crude protein from 820 to 608 g/kg for the diets with increasing proportions of Cocoyam leaves.

It is concluded that the protein in fresh Cocoyam leaves has a high biological value and that the limiting nutritional factor is the lower digestibility of the protein compared with soybean meal.

Key words: Colocacia esculenta, feed intake, fibre, foliages, taro, tropics

Introduction

This paper on the nutritive value for pigs of leaves of New Cocoyam is a contribution to a collaborative program (see http://mekarn.org/proprf/content.htm) aimed to develop locally available protein sources that promise to be viable alternatives to soybean and fish meals in diets for pigs. Foliages from sweet potato (*Ipomoea batatas*) (Le Van Anh 2004; Le Van An et al 2005; Sokha et al 2007), cassava (*Manihot esculenta)* (Bui Huy Nhu Phuc 2006; Nguyen Thi Hoa Ly 2006), mulberry (*Morus* alba) (Chiv Phiny et al 2007a,b) and water spinach (*Ipomoea aquatica*) (Chhay Ty and Preston 2006a,b) have been researched in considerable detail. Attention is now being given to members of the Genus Colocasia (Rodríguez et al 2006; Pham Sy Tiep et al 2006; Ngo Huu Toan and Preston 2007), which are widely distributed in tropical latitudes, often as wild or uncultivated plants.

Taxonomy of the Genus Colocasia

The New Cocoyam (also referred to as "Giant Taro") is a member of the family of Araceae, of which there are one hundred genera and more than fifteen-hundred species. Their preferred habitats are in tropical or subtropical environments which are moist and shady. Some are terrestrial plants while others are vines, creepers, or climbers. Many species of the Araceae are also epiphytes. The major edible species are classified in two tribes and five genera: Lasioideae (*Cyrtosperma* and *Amorphophallus*); and Colocasiodeae (*Alocasia*, *Colocasia*, and *Xanthosoma*). Taro (*Colocasia esculenta* [L.] Schott) is considered as a single polymorphic species.

Taxonomic classification: *Xanthosoma saggitifolium* Schott:

Type: Fanerogamas

Sub-type: Angiospermae

Phylum or division: Mangnoliophyta

Class: Liliopsida (Monocotyledonous)

Order: Arum

Family: Araceae

Genus: Alocasia, Colocasia and Xanthosoma

Species: *Xanthosoma saggitifolium*

Origin and Geographic Distribution

Colocasia is widely distributed in the Indo-Malayan region (India and Bangladesh), Asia, Pacific islands, Egypt and the Mediterranea, Africa, Caribbean and America. *Xanthosoma* is native to South and Central America.

"New Cocoyam" (*Xanthosoma sagittifolium*) can be identified by the presence of a corm (see Figure1a and Photo 1a) which is absent in "Old Cocoyam" (*Colocasia esculenta*) (Figure 1b and Photo 1b).

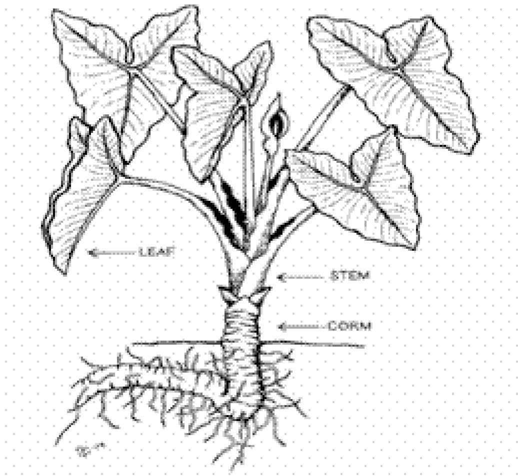

Figure 1a. New Cocoyam or Giant Taro
(*Xanthosoma sagittifolium)*

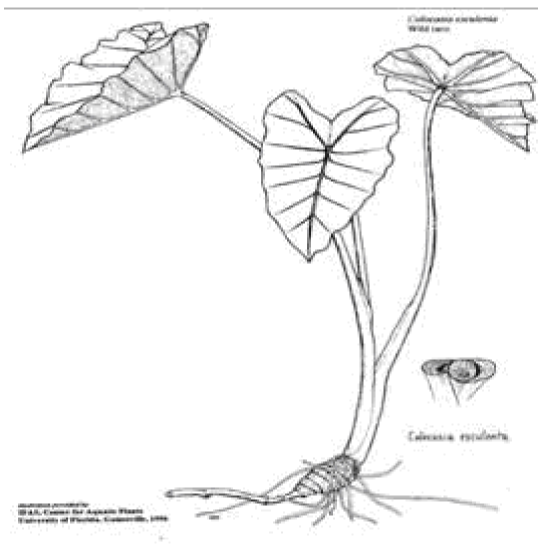

Figure 1b: Old cocoyam or Taro
(*Colocasia esculenta)*

Photo 1a. New Cocoyam or Giant Taro
(*Xanthosoma sagittifolium)*

Photo 1b: Old cocoyam or Taro
(*Colocasia esculenta)*

In a previous study (Rodríguez et al 2006), it was shown that fresh leaves of New Cocoyam (*Xanthosoma saggitifolium*) could replace 50% of the soybean meal with no differences in growth rates or feed conversion in growing pigs fed a basal diet of fresh sugar cane juice. The following experiment was designed to study the effects on apparent digestibility and nitrogen retention of feeding fresh Xanthosoma leaves as a complete replacement of the soybean meal in weaned pigs fed the same basal diet of fresh sugar cane juice.

Materials and Methods

Location

The study was carried out in the "Finca Ecológica", TOSOLY, Morario, Guapota, Department of Santander, Colombia (6° 18" N, 73° 32" W, 1500 msl) between February and May 2006. Air temperature ranges between 19 and 28°C in the day, falling to around 12°C during the night. Rainfall is between 2700 and 3000 mm/year.

Treatments and design

The four treatments (NC0, NC30, NC60 and NC100), applied to 4 growing pigs in a 4*4 Latin square arrangement, were levels of fresh leaves of New Cocoyam equivalent to 0, 30, 60 and 100% substitution of the protein from soybean meal in a basal diet of fresh sugar cane juice. The pigs were crossbred castrated males (Yorkshire*Landrace*Pietran) with initial weight of 13.4±0.54 kg. They were maintained in metabolism cages made from wood and bamboo in which they were able to move freely (Photos 2a and 2b). Experimental periods were of 14 days with collection of faeces and urine during the last 5 days of each period.

Photo 2a: Metabolism cage made from wood and bamboo

Photo 2b: The pigs can move freely in the cage

Diets and feeding

The recently weaned piglets were bought from a commercial farm where they had been fed with commercial concentrates. As soon as they arrived at the TOSOLY farm they were offered fresh New Cocoyam leaves and sugar cane at increasing levels, replacing the commercial concentrate. The piglets accepted immediately the sugar cane juice but acceptance of the leaves was a more gradual process, requiring a period of two weeks before the planned levels of the leaves were consumed. After this period of adaptation, the piglets were put in the metabolism cages.

Leaves plus petioles of New Cocoyam were harvested daily from plants of similar ages (30-35 days cutting interval) located in the farm. The leaves were separated from the petioles and passed first through a mechanical forage chopper. Sugar cane stalks grown on the farm were passed once through a 3-roll mill to separate the juice from the residual fibre (bagasse); the juice was then filtered through a coarse sieve (1 mm holes) and weighed according to the intended offer level. It soon became apparent that there were problems in ensuring accurate measurement of the intakes of the leaves as due to their physical form (as large pieces of 3-5 cm length), the piglets were throwing them out of the feed trough. Furthermore, they much preferred the sugar cane juice and left the leaves to be eaten later. At this stage we decided to mix the leaves with a portion of the sugar cane juice and homogenize the two feeds using a kitchen blender. In this form the piglets readily consumed the leaves and the problem of spillage were avoided.

Soybean meal, or soybean and blended leaves, or blended leaves alone, were given as the first meal at 08.30h. After all the soybean and/or blended leaves/cane juice were consumed the remainder of the cane juice was given. The same procedure was repeated at 15.00h. The proportions of cane juice, soybean meal and leaves, and the amounts offered, were adjusted daily to maintain a crude protein content of 10% in the diet DM and no refusals. The soybean meal was purchased from a commercial supplier in the nearby town of Socorro. A mineral mixture (salt 33.3, rock phosphate 33.3 and magnesium limestone 33.3, parts by weight) was fed daily in quantities equivalent to 1% of the daily DM intake.

Measurements

The pigs were weighed in the morning, before being fed, at the beginning of the trial and after each period of 14 days. Faeces were collected from 530 am to 10 pm every day and were kept frozen in plastic bags until analysis. A representative sample (10% of total amount voided) was obtained from every animal. At the end of each period, the samples of faeces were thawed, mixed thoroughly by hand and then homogenized in a coffee grinder, prior to taking representative samples that were analyzed for DM, N, crude fibre and ash.. Urine was collected in a plastic bucket to which sulphuric acid was added to maintain the pH below 4.0 (10 ml daily of concentrated H_2SO_4), urine pH was measured once at mid day and every morning at weighing time. The volume of urine was measured every day and 10% preserved in a freezer until the end of each period when the samples were mixed together and analyzed for N.

Chemical analyses

Ash, N and crude fibre in feeds and faeces, and N in urine, were determined by the methods of AOAC (1990). DM was determined by micro-wave radiation (Undersander et al 1993).

Statistical analysis

The data were analysed using the General Linear Model of the ANOVA option in he Minitab (2000) software. In the model the sources of variation were: treatments, periods, animals and error. When the “ F” test was significant at the “ 5%” level, the means were separated by the “Tukey” test in the same Minitab software.

Results

There were slight differences between the planned levels of substitution of soybean protein by the protein from New cocoyam leaves (Table 1), with lower than intended levels for the intermediate treatments NC30 and NC60.

Table 1. Proportions (%) of the protein supplement provided by cocoyam leaves and soybean meal; planned and recorded in the experiment

	NC0	NC30	NC60	NC100
Planned	0	30	60	100
Recorded	0	25	53	100

On the NC100 diet (zero soybean meal), New Cocoyam leaves provided almost 50% of the DM (Figure 2) and almost all the crude protein (Figure 3).

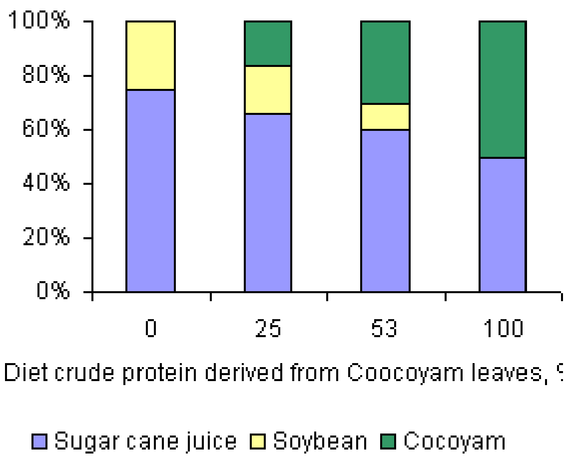

Figure 2: Proportions of diet DM derived from individual ingredients according to level of protein from fresh Cocoyam leaves replacing protein from soybean meal

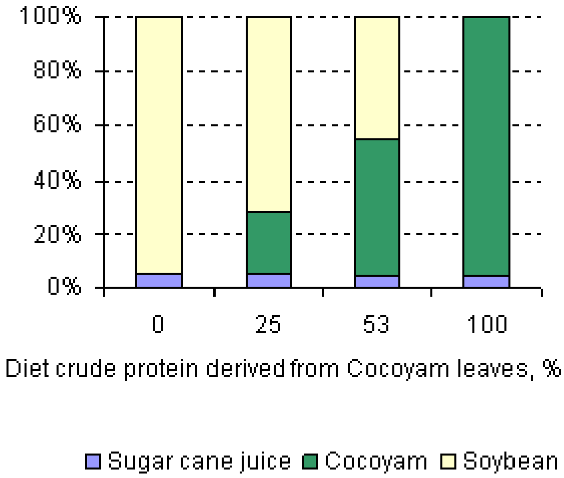

Figure 3: Proportions of diet crude protein derived from individual ingredients according to level of protein from fresh Cocoyam leaves replacing protein from soybean meal

DM intake was relatively high on all the diets (range from 48 to 56 g/kg DM/kg), the lowest value being recorded on the diet with 100% replacement of soybean protein by Cocoyam leaves but with no differences among the other diets (Table 2). Intake of N was similar on diets NC0 and NC30 but then decreased significantly on diet NC60 with a further decrease on diet NC100. The crude protein concentration in the diet declined from 142 g/kg DM on the NC0 diet to 108 g/kg DM with the complete replacement of soybean by Cocoyam leaves (NC100).

Coefficients of apparent digestibility of DM, OM and crude protein were high on all diets (Table 2) with negative linear trends (Figures 4, 5 and 6) as the proportion of dietary N from Cocoyam was increased. The rate of decline was more pronounced for apparent digestibility of crude protein compared with DM and OM.

Table 2. Mean values for feed intake, apparent digestibility of DM and crude protein and nitrogen balance in young pigs fed sugar cane juice and increasing proportions (0 to 100%) of protein from fresh leaves of New Cocoyam (NC) replacing protein from soybean meal

	NC0	NC30	NC60	NC100	SEM	Prob.
Intake, kg/day						
Sugar cane juice	3.07a	3.09a	2.37b	1.90c	0.70	0.001
Cocoyam leaves	0.00	0.791	1.39	2.30		
Soybean meal	0.246	0.181	0.098	0.000		
DM	0.885ab	0.958a	0.861b	0.812b	0.0210	0.001
DM #	*0.753a*	*0.854b*	*0.911c*	*1.04d*	*0.013*	*0.001*
DM, g / kg LW	52.9a	55.8a	52.4a	48.3b	1.10	0.001
DM, g / kg LW #	*48.8*	*52.7*	*53.7*	*55.4*	*1.09*	*0.001*
N*6.25 in diet DM, g/kg	142a	126b	121b	108c	0.19	0.001
Apparent digestibility, g / kg						
DM	939a	912a	882b	832c	8.00	0.001
OM	920a	881ab	865b	802c	9.2	0.001
N*6.25	820a	752b	685b	608c	18.6	0.001
N balance, g / day						
Intake	19.5a	19.0a	16.5b	13.5c	0.331	0.001
Faeces	3.60a	4.80b	5.20b	5.47b	0.32	0.001
Urine	7.07a	4.54b	3.90b	2.09c	0.30	0.001
Urine#	*6.55a*	*4.15b*	*4.04b*	*3.06b*	*0.40*	*0.001*
N retained						
N retained, g/day	8.84a	9.71a	7.37b	6.00c	0.47	0.001
N retained, g/day #	*7.63*	*8.75*	*7893*	*8.04*	*0.65*	*0.26*
N retained / N intake	0.465	0.511	0.454	0.442	0.024	0.21
N retained / N digested	0.564a	0.673b	.0.658b	0.713b	0.022	0.001
N retained / N digested #	0.551a	0.662b	0.664b	0.736b	0.030	0.001

 # Adjusted by covariance for differences in total N intake; abcd Mean values within rows without common letter are different at P<0.05

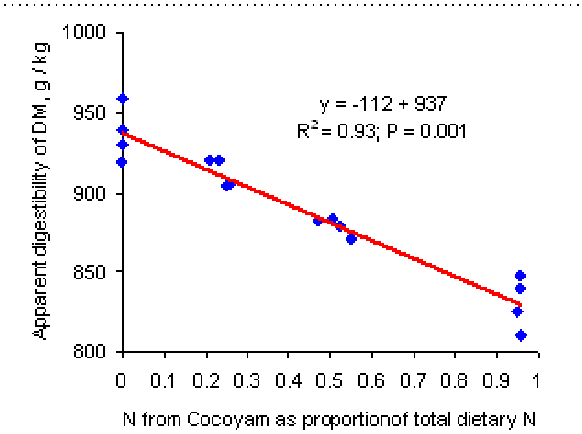

Figure 4: Relationship between dietary N derived from New Cocoyam and apparent digestibility of DM in young pigs fed sugar cane juice and increasing proportions of protein from fresh leaves of New Cocoyam replacing protein from soybean meal

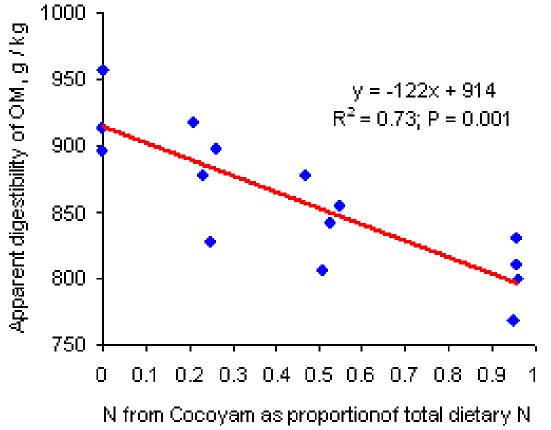

Figure 5: Relationship between dietary N derived from New Cocoyam and apparent digestibility of OM in young pigs fed sugar cane juice and increasing proportions of protein from fresh leaves of New Cocoyam replacing protein from soybean meal

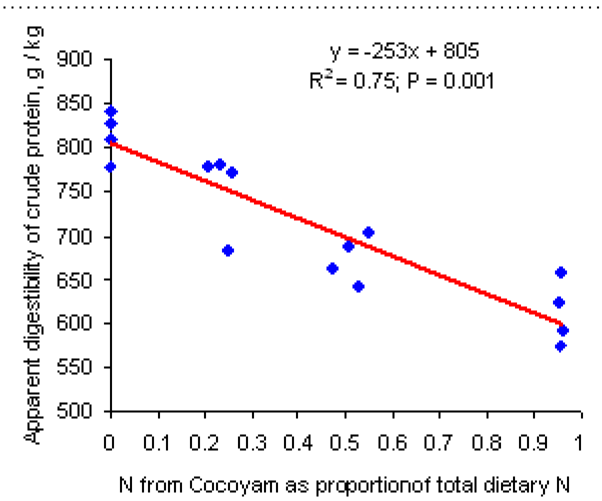

Figure 6: Relationship between dietary N derived from New Cocoyam and apparent digestibility of crude protein in young pigs fed sugar cane juice and increasing proportions of protein from fresh leaves of New Cocoyam replacing protein from soybean meal

There were significant effects of N intake on DM intake (Figure 7), urine N excretion (Figure 8) and N retention (Figure 9). Adjusting the data for these variables by covariance for differences in N intake changed markedly the treatment effects on DM intake and N retention. After adjustment, DM intake was highest for NC100 and lowest for NC0, while N retention was similar on all diets (Table 2).

N retention as a proportion of N digested was significantly higher for the diets containing Cocoyam leaves compared with the NC0 diet in which all the protein was derived from soybean. The pathway of excretion of dietary N differed markedly among diets (Figure 10).

As the level of cocoyam protein in the diet increased, the proportion of dietary N excreted in faeces increased while the proportion excreted in the urine decreased.

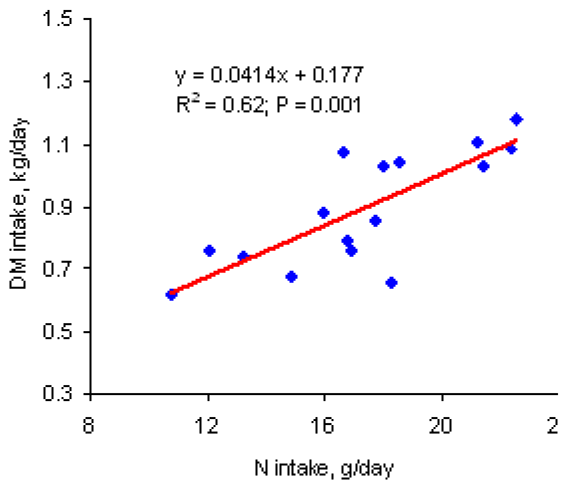

Figure 7: Relationship between N intake and DM intake in young pigs fed sugar cane juice and increasing proportions (0 to 100%) of protein from fresh leaves of New Cocoyam replacing protein from soybean meal

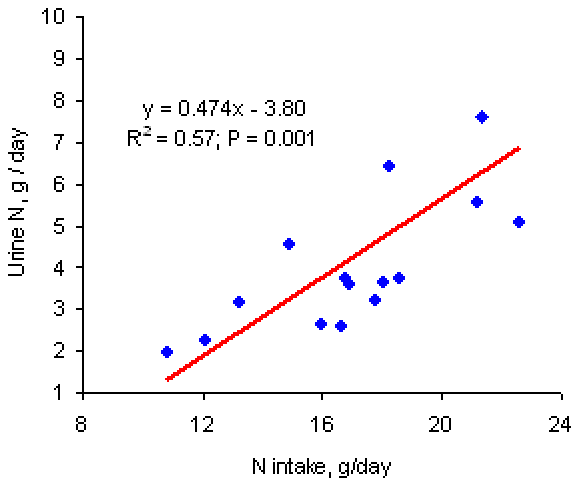

Figure 8: Relationship between N intake and urine N excretion in young pigs fed sugar cane juice and increasing proportions (0 to 100%) of protein from fresh leaves of New Cocoyam replacing protein from soybean meal

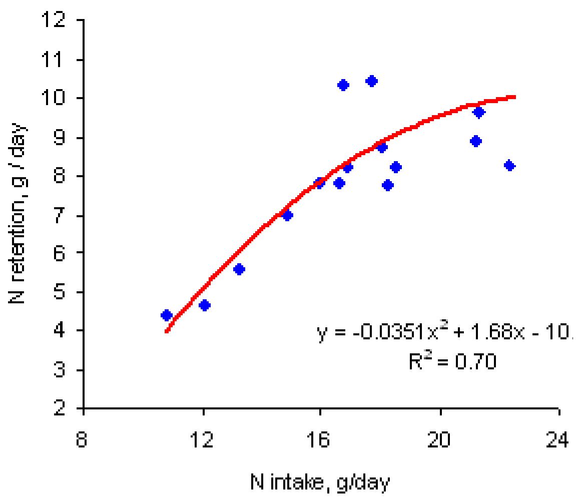

Figure 9: Relationship between N intake and N retention in young pigs fed sugar cane juice and increasing proportions (0 to 100%) of protein from fresh leaves of New Cocoyam replacing protein from soybean meal

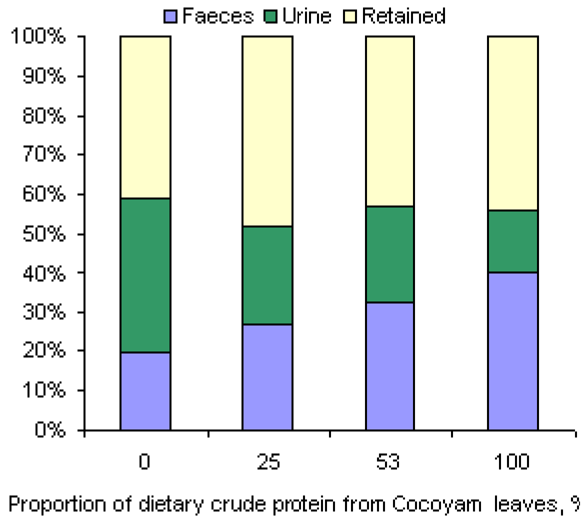

Figure 10: Proportions of dietary N excreted in faeces and urine and retained in young pigs fed sugar cane juice and increasing proportions of protein from fresh leaves of New Cocoyam replacing protein from soybean meal

Discussion

Attempts were made to control the intakes of sugar cane juice, soybean meal and Cocoyam leaves so as to achieve the desired proportions of these three ingredients in the diets. However, this was only partially successful with the result that proportions of protein from Cocoyam leaves were less than planned for treatments NC30 and NC60, while total N intakes were less than planned for diets NC60 and NC 100. The significant relationships between N intake and both DM intake and N retention imply that if the crude protein level in diet NC100 had been higher then the N retention response would also have been higher. This hypothesis will be tested in a subsequent experiment.

A related study to determine the nutritive value of New Cocoyam leaves (*Xanthosoma sagittifolium*) was reported by Leterme et al (2005). However, the nature of the basal diet used by these authors was quite different to the present work in that the energy component was based on maize grain (40% of the diet DM) and the New Cocoyam leaves supplied 35% of the diet DM. As a result the NDF content of their diet DM was 27% compared with 12.7% in the diet of the present experiment, this lower fibre level being possible through use of sugar cane juice as a fibre-free energy source. This difference in levels of NDF could the major reason why Leterme et al (2005) found that their pigs, although heavier (34 kg) and therefore older, would not eat more than 35% of the diet in the form of Cocoyam leaves. In the present study with younger and lighter pigs (20 kg on average) the leaves represented 50% of the diet DM in the NC100 treatment and overall DM intakes were high (>40 g DM/kg live weight). There were also major differences in the apparent digestibility of the crude protein of the Cocoyam leaves which was calculated to be only 340 g/kg in the study of Leterme et al (2005) compared with a value of 600 g/kg in the present study. As a result Leterme et al (2005) estimated the digestible crude protein (DCP) of the leaves to be only 57 g/kg DM while in the present study the comparable value was 130 g DCP/kg DM. Leterme et al (2005) calculated the digestibility of the leaves by the "difference" method, in which the digestibility of the basal diet is determined separately and is assumed to be the same when combined with the leaves. In the present experiment, all the protein in diet NC100 was derived from Cocoyam leaves thus the directly measured estimate of digestibility is likely to be a truer estimate of the nutritive value of the leaves.

The N retained as a proportion of the N digested was 26% greater on the diet with 100% Cocoyam protein compared with the 100% soybean diet (unadjusted data). The difference was even greater (34%) when the values were adjusted for differences in N intake (Table 2). This indicates that the biological value of the Cocoyam protein may well be higher than that of the soybean protein. Data on the ratios of methionine + cysteine as a proportion of the lysine (Table 3), and comparisons with the "ideal protein" and soybean meal, provide supporting evidence of the high biological value of the protein in New Cocoyam leaves.

Table 3. Crude protein and NDF content and ratios of limiting amino acids in leaves of New Cocoyam (*Xanthosoma sagittifolium*) compared with the ideql protein and soybean meal

	Proportion of lysine = 1		g/kg DM	
	Meth + Cyst	Threonine	CP	NDF
Ideal protein #	0.59	0.75		
Rodríguez et al 2006	0.58	0.71	248	255
Leterme et al 2005	0.55	0.75	235	273
Soybean meal ##	0.45	0.62	515	

Wang and Fuller *1989; ## Martin 1990*

The limiting factor in the New Cocoyam leaves is almost certainly the low digestibility of the protein, with N retention being closely related to the intake of apparently digestible crude protein (Figure 11).

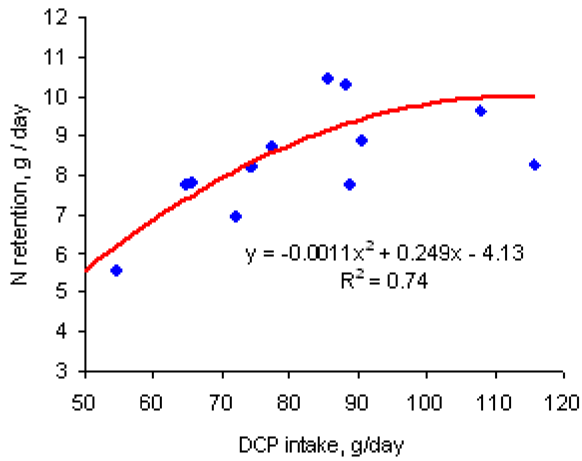

Figure 11: Relationship between digestible crude protein (DCP) intake and N retention in young pigs fed sugar cane juice and increasing proportions (0 to 100%) of protein from fresh leaves of New Cocoyam replacing protein from soybean meal

Chittavong Malavanh et al (2007a) fed Mong Cai gilts on diets in which the energy component was from ensiled cassava roots and broken rice with 70% of the protein provided either by a 50:50 mixture (DM basis) of ensiled Cocoyam leaves (*Colocacia esculenta*) and fresh water spinach (I*pomoeoa aquatica*) or soybean meal. There were no differences in reproduction traits but weight loss during lactation was increased and piglet growth rate to weaning decreased on the diet with the cocoyam leaves and water spinach. These authors also concluded that the lower apparent digestibility of this diet (595 g/kg) compared with that on the soybean diet (816 g/kg) was probably the major reason for the poorer performance on the former diet (Chittavong Malavanh et al (2007b).

Conclusions

- The high DM intakes (>5% of LW) with fresh cocoyam leaves providing 47% of the total DM intake in basal diet sugar cane juice are because:
  - The sugars are rapidly digested?
  - The fine particle size of the leaves (after blending of leaves with the sugar cane juice + minerals)?
  - The low fibre content of the leaves?
- The protein in the fresh Cocoyam leaves appears to have a high biological value at least equal to that in soybean
- The limiting nutritional factor in fresh cocoyam leaves is the lower digestibility of the protein (61%) versus soybean (81%).

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Chapter 5. Studies on the nutritive value for pigs of New Cocoyam (*Xanthosoma sagittifolium*); digestibility and nitrogen balance with different levels of ensiled leaves in a basal diet of sugar cane juice

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Abstract

Four crossbred (Yorkshire*Landrace*Pietran) castrated male pigs with initial weight of 18.7±3.2 kg (mean ± SD) received varying proportions of ensiled New Cocoyam (*Xanthosoma sagittifolium*) leaves (ENCL) and fresh sugar cane juice in two consecutive periods to provide different levels of crude protein in the range of 80 to 160 g/kg of diet DM. In period 1, the planned levels were: 100, 120, 140 and 160 g/kg DM; in period 2 these were changed to 90, 110, 130 and 150 g/kg DM. The fresh sugar cane juice contained 20 to 21% total sugars. The Cocoyam leaves were macerated in a high-speed mechanical chopping machine and ensiled with addition of 10% (fresh basis) of sugar cane juice.

The leaf silage was of excellent quality as judged by smell and colour and the rapid fall in pH (< 4) within 3 days of ensiling the leaves. Recorded proportions of ENCL in diet DM were 0.49, 0.56, 0.67 and 0.76 in period 1 and 0.46, 0.48, 0.57 and 0.67 in period 2. DM intake was high on all diets (range from 32 to 53 g/kg LW) and showed a curvilinear response to increasing proportions of ENCL in the diet, with a maximum value at 0.55 of ENCL in diet DM. Apparent digestibility of DM decreased, and that of crude protein increased, as the proportion of ENCL in the diet DM increased. N retention increased with increasing proportion of ENCL in the diet, the relationship being curvilinear with the maximum value at 0.67 ENCL, equivalent to 130 g crude protein per kg of diet DM.

Key words: Curvilinear response, dry matter intake, N intake, production function design

Introduction

In a previous study in this series of experiments on the nutritive value of leaves of New Cocoyam (*Xanthosoma sagittifolium*) for pigs (Rodríguez et al 2009), it was postulated that the major constraint to their nutritive value as a replacement for soybean meal was the digestibility of the protein; by contrast the biological value of the protein appeared to be comparable to that in soybean. Because of the lower digestibility of the protein, and the decision in that study to fix the dietary crude protein level to 10% of the dry matter, the intake of digestible crude protein (DCP) decreased curvilinearly as soybean was replaced by New Cocoyam leaves. In the diet with 100% replacement of soybean by New cocoyam leaves, the intake of DCP was only half that on the 100% soybean treatment. It was hypothesized that it was the low intake of digestible crude protein that was responsible for the lower N retention on the diet with 100% fresh Cocoyam leaves compared with the diet containing soybean meal.

In the previous study (Rodríguez et al 2009), the Cocoyam leaves were processed in a kitchen blender along with small quantities of sugar cane juice. This procedure is not suitable under practical conditions as “kitchen” blenders cannot deal with large quantities of material and industrial machines are expensive. It was therefore decided that for future studies it was more appropriate to use a high-speed cropping machine (TORMETAL SA; 3500 rpm), which it had been shown effectively macerates leaf material into very small pieces. Recent reports from

Vietnam (Pham Tiep et al 2006; Du Thang Hang and Preston 2007) with leaves from Giant Taro (*Alocacia macrorrhiza*) showed the advantages from ensiling the leaves compared with feeding them fresh, as a means of reducing the concentration of calcium oxalate, which causes "itchiness" in the mouth and on the skin when the leaves are fed fresh. Ensiling is also a convenient management practice as harvesting can be programmed at appropriate intervals to take advantage of the normal life cycle of the leaves which lasts on average some 25 days.

The objective of the present study was therefore to determine the effect on nitrogen retention in young pigs of varying the level of ENCL in a basal diet of sugar cane juice to provide a range of crude protein in diet DM of between 100 and 150 g/kg.

Materials and methods

Location

The study was carried out in the "Finca Ecológica", TOSOLY, Morario, Guapota, Department of South Santander, Colombia (6° 18" N, 73° 32" W, 1500 msl) between February and May 2006. Air temperature ranges between 19 and 28°C in the day, falling to around 12°C during the night. Rainfall is between 2700 and 3000 mm/year.

Treatments and design

Four crossbred (Yorkshire*Landrace*Pietran) castrated male pigs with initial weight of 18.7±3.2 kg (mean ± SD) received varying proportions of ensiled New Cocoyam (*Xanthosoma sagittifolium*) leaves in two consecutive periods to provide different levels of crude protein in the range of 80 to 160 g/kg of diet DM. In period 1, the planned levels were: 100, 120, 140 and 160 g/kg DM; in period 2 they were 90, 110, 130 and 150 g/kg DM. The energy component of the diet was fresh sugar cane juice. The pigs were maintained in metabolism cages designed for separate collection of urine and faeces (Rodríguez et al 2009). The experimental periods were of 14 days with collection of faeces and urine during the last 5 days of each period.

Diets and feeding

Leaves plus petioles of New Cocoyam were harvested from plants of similar ages located in the farm. The leaves were separated from the petioles and passed through a high-speed (3500 rpm) mechanical ensiling machine (Photo 1) which macerated the leaves into very small particles (Photo 2). The macerated leaves were then mixed with 10% of fresh sugar cane juice and ensiled in air-tight rigid plastic containers (Photos 3 y 4). Stalks of sugar cane, grown on the farm, were passed once through a 3-roll mill to separate the juice from the residual fibre (bagasse). Half the daily allowance of ensiled leaves was mixed with equal parts (fresh basis) of fresh sugar cane juice and given as the first meal at 7.00am. After all the ensiled leaves/cane juice mixture was consumed the remainder of the allowance of cane juice (the allowance was 50%of the intended daily intake) was given. The same procedure was repeated at 15.00h. The proportions of cane juice and ensiled leaves were fixed to maintain the crude protein content of the diets at the programmed levels. The amounts offered were adjusted daily according to the appetite of the pigs so that there were no refusals. A mineral mixture (salt 33.3, rock phosphate 33.3 and magnesium limestone 33.3, parts by weight) was fed daily in quantities equivalent to 1% of the daily DM intake.

Photo 1. New Cocoyam leaves processed by a high-speed (3500 rpm) mechanical ensiling machine

Photo 2. New Cocoyam leaves mixed with 10% of fresh sugar cane juice and ensiled in air-tight rigid plastic containers

Photo 3. New Cocoyam leaves + Sugar Cane Juice ensiled in air-tight rigid plastic containers

Photo 4. New Cocoyam leaves ensiled for one week

Measurements

The pigs were weighed in the morning, before being fed, at the beginning and end of each period. Representative samples of silage were taken at the beginning of the experiment for determination of DM, nitrogen and ash. The brix (% sugars) of the sugar cane juice was determined daily. During the 5-day collection period, faeces were collected at intervals during the day and night and were kept frozen in plastic bags until analysis. A representative sample (10% of total amount voided) was obtained from every animal. At the end of each period, the samples of faeces were thawed, mixed thoroughly by hand and then homogenized in a coffee grinder, prior to taking representative samples that were analyzed for DM, N, crude fibre and ash. Urine was collected in a plastic bucket to which sulphuric acid (10 ml daily of concentrated H_2SO_4) was added to maintain the pH below 4.0. The volume of urine was measured every day and 10% preserved in a freezer until the end of each period when the samples were mixed together and analyzed for N.

Chemical analyses

Ash, N and crude fibre in feeds and faeces, and N in urine, were determined by the methods of AOAC (1990). DM was determined by micro-wave radiation (Undersander et al 1993). The brix of the sugar cane juice was measured with a hand refractometer.

Statistical analysis

The data were subjected to regression analysis (Excel in Microsoft Office 2003 Software), in which the independent variables were proportion of diet DM from ensiled ENCL (or crude protein intake per kg live weight) and the dependent variables were the various measures of animal response (feed intake, apparent digestibility and N balance).

Results

Ensiling Cocoyam leaves

Despite the relatively low DM content (13.5%), the New Cocoyam leaves, the silage was of excellent quality as judged by smell and colour and the rapid fall in pH (< 4) within 3 days of ensiling the leaves (Figure 1). The Brix of the sugar cane juice was also relatively constant during the experiment (Figure 2).

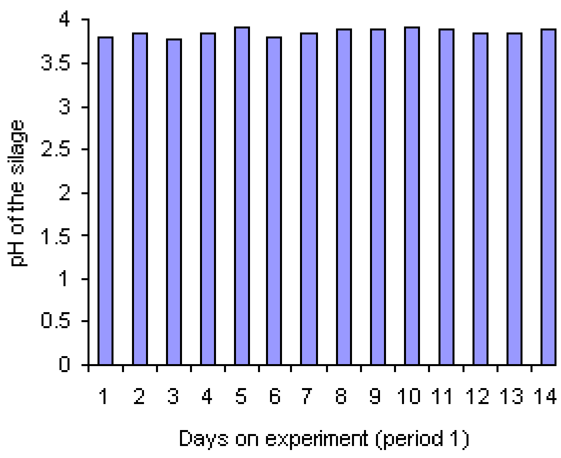

Figure 1. pH of silage in period 1 of the experiment (Data in period 2 were similar)

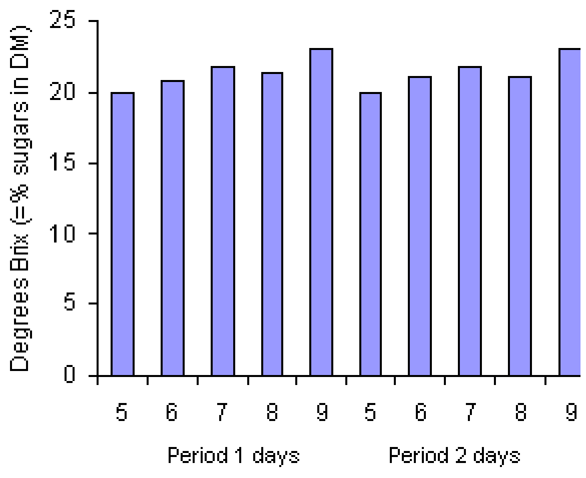

Figure 2. Brix of the sugar cane juice taken during collection days in periods 1 and 2

Feed intake

It was not feasible to offer the diets as complete mixtures of ensiled leaves and sugar cane juice as, when presented in this form in the feed trough, most of the juice separated from the silage, and the pigs were able to consume it first in preference to the silage. The result was variable amounts of refusals of widely different composition. For this reason the procedure was adopted of ensuring that all the allowance of silage (plus limited amounts of juice mixed with it) was consumed before giving the bulk of the cane juice. This method was effective in eliminating feed refusals but made it difficult to ensure that the "planned" proportions of silage and juice were maintained. The result was that the "recorded" ratios were slightly different from the "planned" ratios (Table 1). The recorded ratios were those used as independent variables in the regression analysis.

DM intake as a function of live weight (Table 1) was high on all diets (range from 32 to 53 g/kg LW) and showed a curvilinear response (Figure 3) to increasing proportions of ENCL in the diet. The maximum value was with 55% ENCL in diet DM. The crude fibre in the diet was totally derived from the ensiled Cocoyam leaves and accounted for 9% of the diet DM at the point of maximum DM intake (Figure 4). The ensiled Cocoyam leaf represented from 48 to 76% of the total DM intake, and 100% of the crude protein.

Table 1. Intakes by young pigs of ingredients and proximate components of diets with different levels of crude protein derived from ensiled leaves of New Cocoyam (ENCL); remainder of diet was fresh sugar cane juice,

	Period 1				Period 2			
Crude protein in DM, g/kg								
Planned	100	120	140	160	90	110	130	150
Recorded	87.3	110	131	149	81	100	100	140
Feed intake, g/day								
SC juice	1730	1343	1073	546	1771	2455	848	1992
ENCL	2780	2880	3627	3110	2729	2512	3331	3070
Minerals	17.8	16.8	18.2	14.2	17	19	15	19
DM, g/day								
SC juice	372	287	229	116	379	525	181	426
ENCL	370	388	489	418	439	404	535	493
Minerals	17.5	16.5	17.9	14.0	16.7	18.7	14.7	18.7
Total	760	691	736	548	948	834	938	732
Total OM	683	613	641	468	874	758	852	644
Total CP	70.7	76.1	95.9	81.9	77.1	83.7	94.2	102
Total CF	69.5	75.4	56.9	61.8	56.9	61.8	69.5	75.4
DM, g/kg LW	38.9	53.2	38.8	32.3	42.2	41.8	41.7	45.7
ENCL/total DM	0.487	0.561	0.665	0.762	0.463	0.484	0.571	0.674
Composition of diet consumed, g/kg DM								
OM	900	887	870	854	922	922	922	922
CP	87.3	110	131	149	81.5	101	100	140
CF	71.0	89.6	106	121	60.1	74.1	74.1	103

. LW Live weight, ENCL Ensiled New Cocoyam leaves, SC Sugar cane, OM Organic matter, CP Crude protein, CF Crude fibre

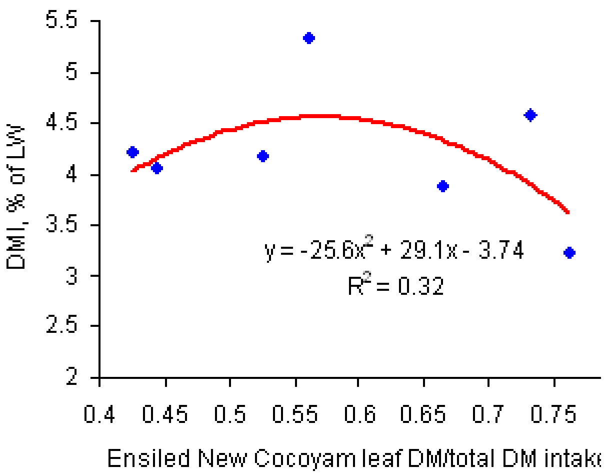

Figure 3. Relationship between proportion of ENCL in the diet DM and DM intake expressed as a function of live weight (periods 1 and 2)

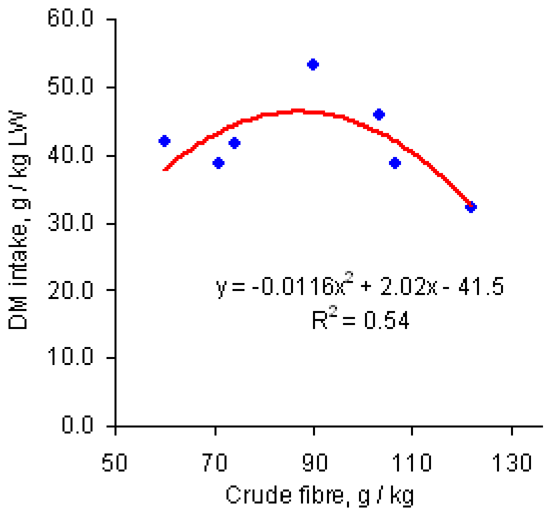

Figure 4. Relationship between crude fibre content of diet and DM intake expressed as a function of live weight (periods 1 and 2)

The apparent digestibility of DM decreased (Table 2; Figure 5) and that of crude protein increased (Table 2; Figure 6), as the proportion of ENCL in the diet DM increased.

Table 2. Apparent digestibility of DM, OM, CP and CF, and N balance data, for young pigs fed diets with different levels of ENCL in a basal of diet of fresh sugar cane juice

	Period 1				**Period 2**			
ENCL in diet DM	0.48	0.56	0.66	0.76	0.46	0.48	0.57	0.67
Live weight, kg								
Initial	20	13	19	17	22.5	20	22.5	16
Final	22.5	16	22.5	20	22.5	20.5	24	17
Daily gain, g	208	250	292	250	0	56	167	111
Apparent digestibility, g/kg								
DM	809	756	741	749	869	855	825	748
OM	829	779	762	761	762	761	829	779
CP	535	516	646	705	478	599	625	587
CF	755	637	594	817	774	825	723	698
N balance, g/day								
Intake	11.3	12.2	15.3	13.1	12.3	13.4	15.0	16.3
Faeces	5.25	5.90	5.45	3.84	6.43	5.37	5.65	6.74
Urine	3.58	2.23	4.39	3.94	2.93	2.38	3.31	2.64
Retention	2.48	4.04	5.51	5.33	2.98	5.66	6.09	6.95
N retent. /N digested	0.59	0.72	0.71	0.70	0.56	0.73	0.67	0.57
Dig CP intake, g/day	47.1	39.2	61.9	57.9	42.5	53.8	63.3	38.2
Dig DM intake, g/day	632	522	544	406	826	693	804	534

Abbreviations are the same as in Table 1.

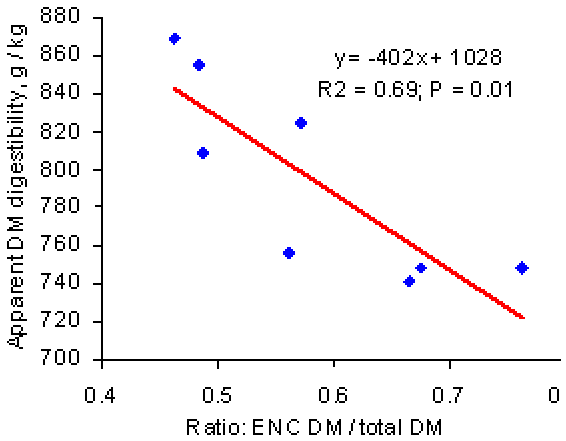

Figure 5. Relationship between proportion of ensiled New Cocoyam leaf (ENC) in the diet DM and apparent DM digestibility

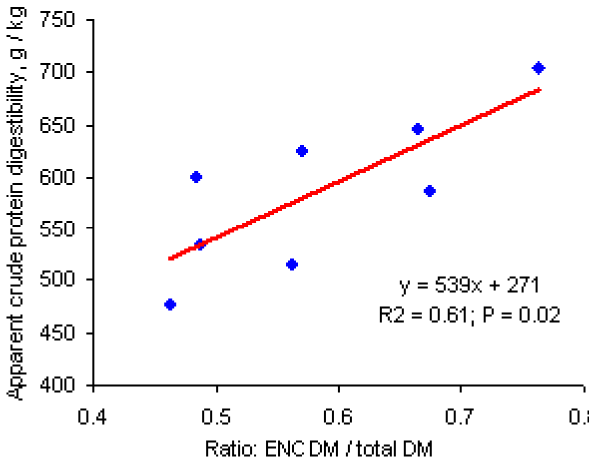

Figure 6. Relationship between proportion of ensiled New Cocoyam leaf (ENC) in the diet DM and apparent crude protein digestibility

From the equation in Figure 5, the apparent DM digestibility of ensiled New Cocoyam leaf can be predicted as the value of "y" when "x"= 1 (ie: with 100% ENCL in the diet). The apparent DM digestibility of ENCL is thus 1028 - (402*1) = 626 g/kg. The other approach is to measure "apparent digestibility" by difference. In this case it is assumed the apparent DM digestibility of sugar cane juice is 100%. Taking the lowest (0.46) and highest values (0.76) for proportion of ENCL in the diet, the associated apparent DM digestibility coefficients of the diets are 839 and 749g/kg DM.

The equation is: Y = ENCL * X + (1-ENCL)*D

Where "X" is apparent DM digestibility of ENCL, "Y" is the apparent digestibility of the diet mixture (expressed as fraction of 1) and "D" is the apparent digestibility of sugar cane juice (=1 as 100% digestible); ENCL is the proportion of ENCL in the diet.

Rearranging the equation

X = (Y-(1-ENCL)*D)/ENCL

For D = 1 and ENCL = 0.46; X = 0.650 (or 650 g/kg)

For D = 1 and ENCL = 0.76; X = 0.670 (or 670 g/kg)

These values are similar to that (626 g/kg) produced by prediction from the linear regression equation in Figure 5.

In a similar way the apparent digestibility of the crude protein in ensiled New Cocoyam leaf can be calculated as: 271+ (539*1) = 810 g/kg.

N balance

N retention increased with increasing proportion of ENCL in the diet, the relationship being curvilinear (Figure 7). The maximum N retention was reached with 65% of ENCL in the diet DM, equivalent to about 5.5 g crude protein per kg of pig LW (Figure 8) and approximately 13% crude protein in the diet DM.

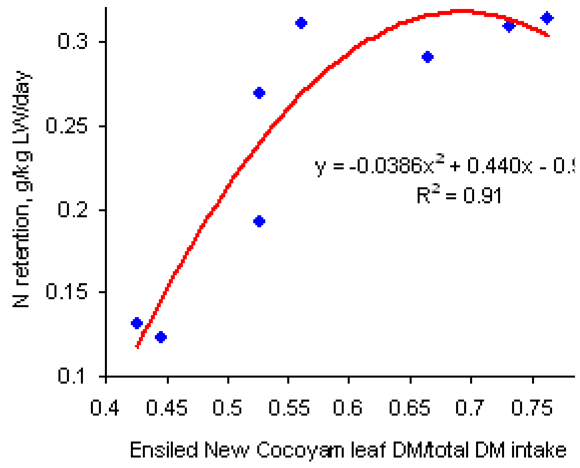

Figure 7. Relationship between proportion of ensiled New Cocoyam leaf (ENCL) in the diet DM and N retention expressed as g N/kg LW

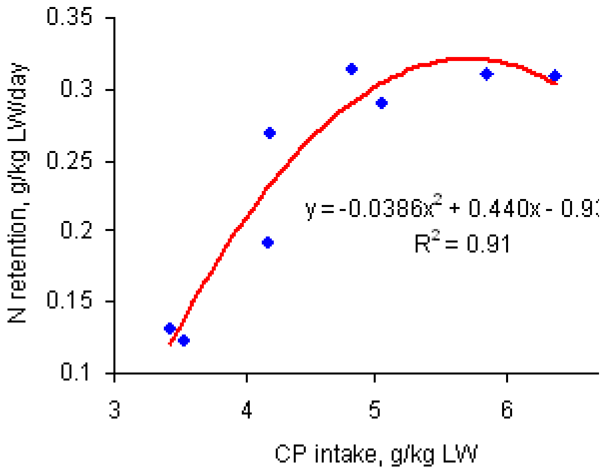

Figure 8. Relationship between intake of crude protein (as g/kg LW) and N retention expressed as g N/kg LW

Discussion

According to McDonald et al (2002), if the material to be ensiled has a relatively low DM content, it is advisable to use an additive with high dry matter content. In preliminary trials with fresh New Cocoyam leaves (containing about 15% DM) we followed this advice and used concentrated sugar cane juice (about 50% sugars) at 4% of the weight of fresh leaves. Subsequently we replaced the concentrated juice with fresh cane juice (about 20% sugars) at 10% of the fresh weight of the leaves with excellent results, the pH falling to below 4.0 in less than 3 days. Similar findings were reported by Chittavong Malaavanh et al (2007) and Du Thanh Hang and Preston (2007) who used 4% molasses to ensile leaves of Taro (*Colocacia esculenta)* and Giant Taro *(Alocacia macrorrhiza*), respectively, plants of the same family as New Cocoyam.

The diets supporting highest DM intakes (close to 50 g/kg live weight) had approximately 55% of the diet DM in the form of ensiled Cocoyam leaves. This indicates that high quantities of protein-rich leaves can be consumed even by young pigs when the energy component of the diet is devoid of fibre, as is the case with sugar cane juice.

The recorded apparent digestibility of the diet DM (820 g/kg DM) when the Cocoyam leaf silage provided 50% of the diet DM is similar to the value (832 g/kg DM) reported in our previous experiment (Rodriguez et al 2007) in a similar diet containing equal quantities of DM from fresh Cocoyam leaves and sugar cane juice.. The predicted range in apparent digestibility of 626 to 670 g/ kg DM for the ensiled Cocoyam leaves as the only diet is slightly higher than was predicted for duckweed (*Lemna minor*) (610 g/kg DM) as the sole diet using a similar experimental design with sugar cane juice as the energy source (Rodriguez and Preston 1996).

The increase in the apparent digestibility of the crude protein of the ensiled Cocoyam leaves as their level in the diets increased presumably reflects the reduction in the proportion of total faecal N provided by endogenous N. At levels of 50% of ensiled Cocoyam leaves in the diet DM the apparent crude protein digestibility was slightly lower (530 g/kg) than that reported in the previous experiment (Rodriguez et al 2007) with a diet of the same composition.

The maximum level of N retention (0.35g/kg live weight) with 65% is similar to that reported by Rodríguez et al (2009) for a diet with 55% of the DM as fresh leaves of New Cocoyam (0.38g N/kg live weight), in both cases with fresh sugar cane juice as the basal diet.

An optimum crude protein content of between 130 and 140 g/kg DM was found by Sokha et al (2007) for crossbred pigs of similar live weight (average 23 kg) fed low-protein basal diets of cassava root meal with rice bran (50:50), or broken rice, with the protein supplied by a mixture of fresh sweet potato vines and water spinach (50:50 DM basis). This result is similar to what was found in the present study with ensiled New Cocoyam leaves as the protein source (130 g crude protein/kg DM).

Conclusions

- Fresh leaves of New Cocoyam were ensiled satisfactorily with 10% of sugar cane juice (fresh basis), the pH falling to less than 4.0 within 3 days
- Growing pigs (23 kg live weight) were able to consume diets containing up to 80% of the DM as ensiled New Cocoyam leaves at levels close to 40 g DM/kg live weight
- Maximum N retention was achieved with the ensiled New Cocoyam leaves providing 65% of the diet DM, providing a protein level of 130 g/kg diet DM and 5 g crude protein per kg live weight.

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Chapter 6. Effect of biochar and biodigester effluent on growth of maize in acid soils

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Abstract

The hypothesis that was tested in the present study was that there would be a synergistic response in growth of maize when biodigester effluent, rich in NH_4-N, was combined with biochar, derived by gasification of sugar cane bagasse. Two experiments were carried out to measure changes in soil fertility as a function of the growth of maize plants over a 30-40 day period following seeding. In each experiment a completely randomized design was used with 4 replications of the treatments applied to samples of soil held in one litre capacity plastic bags. In experiment 1, 8 treatments were compared in a 2*2*2 factorial arrangement. The factors were: with or without biochar at 50g/kg soil; fertile soil or sub-soil; and with or without biodigester effluent (100 kg N/ha). In experiment 2, ash from a wood-burning stove replaced the biochar used in experiment 1.

Biochar increased green biomass growth of the maize on the fertile soil in absence or presence of biodigester effluent and in the sub-soil when effluent was applied, but had no effect on heavily leached soil without effluent. Application of effluent had no effect on green biomass growth in the fertile soil irrespective of the presence or not of biochar. By contrast, the effluent dramatically increased green biomass growth when biochar was applied to the sub-soil but had no effect in the absence of biochar. Effects on growth of the roots mirrored those on the green biomass except in the case of the sub-soil without effluent when the biochar markedly increased root growth. Soil pH was increased from 4-4.5 to 6.0-6.5 due to addition of biochar. Wood ash brought about increases in the weight of both the aerial part and roots of the maize but the relative increases were only half of those observed when biochar was used. Soil pH was increased to values between 9 and 10.

It is concluded that there are synergistic effects on plant growth in heavily leached, acid soils when biodigester effluent is combined with biochar produced by gasification of sugar cane bagasse.

Key words: Ash, bagasse, biomass, biotest, gasifier, roots, sugar cane, wood stove

Introduction

Recent interest in the use of biochar as a soil amender (Lehmann et al 2006; Lehmann 2007) has its origin in the discovery, by Dutch soil scientist Wim Sombroek in the 1950's, of pockets of rich, fertile soil in the Amazon rainforest (otherwise known for its poor, thin soils). He gave it the name of *Terra Preta* ("black earth"). Carbon dating has shown that the carbon in these soils dates back to between 1,800 and 2,300 years (Glaser 2007).

Terra preta is rich in minerals including potassium, phosphorus, calcium, zinc, and manganese - however it's most important ingredient is charcoal, the source of *terra preta's* dark colour. The exact origin of the charcoal in *Terra preta* is not fully understood but it appears to have arisen from controlled burning of trees and related biomass sources. The fact that it has remained in the soil for thousands of years implies that it can be an effective medium for long term sequestration of carbon derived originally from the atmosphere through photosynthesis. This also indicates that the form of the charcoal in *Terra preta* soils is different to the charcoal prepared in the traditional manner as a source of fuel for cooking. This has given rise to the term "biochar" to differentiate this "stable" form of charcoal, that is not oxidized by soil micro-organisms, as compared with charcoal which eventually is degraded by soil microbes to carbon dioxide. According to Glaser (2007) the chemical structure of biochar is characterized by the presence of poly-condensed aromatic moieties and that these are responsible for the stability against microbial degradation.

The apparent high fertility of *Terra preta* soils,, has led to research to measure the immediate effects of "biochar" addition to soils on plant growth. Major increases (up to 324%) in yield of a range of crops through addition of biochar at rates varying from 0.5 to 135 tonnes/ha were recorded in the review by Sohi et al (2009). However, these authors state that addition of nutrients from inorganic or organic fertilizers is usually essential for high productivity and to increase the positive response from the bio-char amendment. Chan et al (2008) recorded a linear increase in yield of radish (*Raphanus sativus*) by addition of up to 50 tonnes/ha of biochar provided additional N fertilizer was also supplied. Glaser (2007) also indicated that there would be benefits in plant growth from combining the biochar with chicken manure.

The explanations for the effects of addition of biochar to soils in increasing crop yields include greater water holding capacity, increased Cation Exchange Capacity (CEC), and providing a medium for adsorption of plant nutrients and improved conditions for soil micro-organisms (Sohi et al 2009). Biochar efficiently adsorbs ammonia (NH_3) according to Oya and Iu (2002) and Iyobe et al (2004) and acts as a binder for ammonia in soil, therefore having the potential to decrease ammonia volatilization from soil surfaces .

Biodigestor effluent from livestock excreta contains a high proportion of the nitrogenous constituents as ammonium salts. Pedraza et al (2002) observed that the proportion of ammonia-N in the effluent from plug-flow, tubular plastic biodigesters was in the range of 0.65 to 0.75. Similar findings were reported by San Thy et al (2003). In their study, the proportion of ammonia-N to total-N increased from 0.077 to 0.12 in fresh pig manure to 0.46 to 0.65 in the effluent. The combination of biodigester effluent and biochar therefore should be synergistic in improving soil fertility and plant growth

The hypothesis that was tested in the present study was that there would be a synergistic response in growth of maize when biodigester effluent is combined with biochar.

Materials and methods

Location

The study was carried out in the "Finca Ecológica", TOSOLY, Morario, Guapota, Department of South Santander, Colombia (6° 18" N, 73° 32" W, 1500 msl) between September and December 2008. Air temperature ranges between 19 and 28°C in the day, falling to around 12°C during the night. Rainfall is between 2700 and 3000 mm/year and is relatively evenly distributed.

Treatments and design

Two experiments were carried out using the maize "biotest" for measuring changes in soil fertility as a function of the growth of maize plants over a 30-40 day period following seeding (Boonchan Chantaprasarn and Preston (2004). In each experiment a completely randomized design was used with 4 replications of the treatments applied to samples of soil held in one litre capacity plastic bags (Photo 1).

Photo 1. General view of the layout of the "biotest"

Experiment 1: Effect of biochar added to soil (pH 4.0) at 50 tonnes/ha with and without biodigester effluent (100 kg N/ha) on growth of maize

Eight treatments were compared in a 2*2*2 factorial arrangement with 4 replications.

The factors were:

Biochar: With or without biochar

Soil type: Fertile soil or sub-soil

Biodigester effluent: With or without effluent

Experiment 2: Effect of wood ash added to soil at 50 tonnes/ha with or without biodigester effluent

The eight treatments and the design were the same as in Experiment 1 but with wood ash replacing the biochar. The factors were:

Wood ash: With or without

Soil type: Fertile soil or sub-soil

Biodigester effluent: With or without

Materials

Biochar

The biochar (Photo 2) was the solid residue from a down-draft gasifier (Photo 3; Ankur PTY, India), charged with sugar cane bagasse derived from sugar cane stalks passed two times through a 3-roll crusher driven by a diesel engine (Photo 5). It contained 35% ash and 65% carbon and had a pH of 9.0. The bagasse was sun-dried to about 12% DM and hand-separated into large and small pieces, the latter being the feedstock for the gasifier. The particle size of this fraction was between 1 and 30mm (Photo 4). After gasification of this fraction the residual biochar represented 10% by weight of the air-dry bagasse (88% DM) fed into the gasifier.

Photo 2. Biochar produced by gasification of sugar cane bagasse

Photo 3. T he downdraft gasifier (Ankur Technologies) used to produce the biochar as a byproduct of electricity generation

Photo 4. Sugar cane bagasse used in the gasifier

Photo 5. The three-roll crusher ("trapiche") used to fractionate the sugar cane stalks into juice (for feeding pigs and people) and residual bagasse

Wood ash

This was the residue after burning firewood in a closed stove (Photo 6). The pH was 9.5.

Soil samples

Two types of soil were used in each experiment. The fertile soil was taken from areas (top 10cm) in a coffee plantation shaded with Guamo trees (*Inga hayesii* Benth) (Photo 7). The pH of this soil was 4.5. The second sample (sub-soil) was from soil that had been excavated during construction work (Photo 8). The pH was 4.0.

Samples (about 1 kg) of the respective soils were placed in polyethylene bags with or without addition of the biochar (or ash) which was mixed thoroughly with the soil according to the imposed treatment. Water was sprayed uniformly on the bags at 2-day intervals throughout the growth period of 40 days.

Photo 6. The wood stove used to produce the ash used in Experiment 2

Photo 7. The coffee plantation from where fertile soil was taken

Photo 8. The origin of the sample of sub-soil

Photo 9. The plug-flow tubular polyethylene biodigester

Biodigester effluent

The effluent was taken from the exit stream of a "plug-flow" tubular polyethylene (3.0 m^3 liquid volume) biodigester (Photo 9) charged daily with the washings (500 litres) from 4 pens each holding on average 8 pigs of 50 kg mean live weight. The diet of the pigs (DM basis) on average contained 20% soybean meal, 30% rice polishings and 50% fresh sugar cane juice. The N content of the effluent was 700 mg/litre with 420 mg/litre as NH_4-N. It was poured on the surface of the soil in the bags at weekly intervals (5 applications) at the overall rate of 100 kg N/ha. Similar amounts of water were added to the bags not receiving effluent.

Maize seeds

These were of a local variety. Three seeds were placed in each bag. After germination, one or two seedlings were removed to leave only one plant for the experimental growth period of 40 days.

Measurements

At 40 days after seeding the height of the maize was measured at the tip of the highest leaf. The complete plant was then removed from the bag and the aerial part separated from the roots which were washed free of soil. Both fractions were weighed. The pH of the soil was measured with a digital pH meter at the time of harvesting the maize.

Statistical analysis

The data were analysed using the General Linear Model in the ANOVA option of the Minitab (2003) software. Sources of variation were: Blocks, Biochar, Effluent, Soil type, and the interactions of Biochar*Effluent, Biochar*Soil, Effluent*Soil, Biochar*Effluent*Soil and error.

Results

Effects of biochar

The height and the fresh weights of the aerial part and the roots of the maize were increased by addition to the soil of biochar and biodigester effluent and were higher for the maize grown in the fertile compared to the sub-soil (Table 1). Soil pH was increased by addition of biochar and was higher in the fertile soil.

Table 1. Mean values for effects of biochar, effluent and soil type on height and fresh weights of aerial part and roots of maize, and on soil ph (after 40 days growth of the maize)

	Height, cm	**Aerial part, g**	**Roots, g**	**Soil pH**
Biochar				
With	53.4	30.3	38.4	6.33
Without	27.1	5.78	10.1	4.58
P	0.001	0.001	0.001	0.001
Effluent				
With	48.0	25.9	30.4	5.43
Without	32.6	10.1	18.2	5.48
P	0.002	0.001	0.012	0.25
Soil				
Fertile	50.7	23.3	30.5	5.73
Heavily leached	29.9	12.8	18.1	5.17
P	0.001	0.006	0.001	0.001
SEM	3.13	2.41	3.13	0.045
P (interactions)				
B*E	0.14	0.005	0.005	0.27
B*S	0.85	0.66	0.66	0.001
E*S	0.04	0.075	0.075	0.166
B*E*S	0.03	0.011	0.095	0.83

There were interactions due to the treatments on weights of aerial part and roots of the maize (Table 1 and Figures 1 and 2) for biochar*effluent and biochar*effluent*soil type with tendencies for interaction (P=0.075) for effluent*soil.

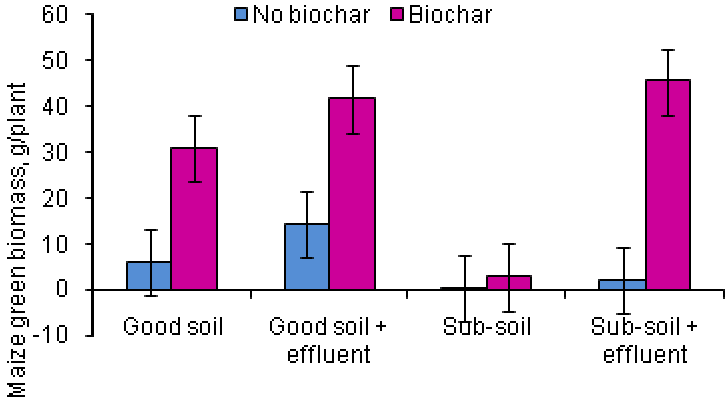


Figure 1. Effect of biochar and effluent added to fertile soil and sub-soil on fresh weight of aerial part of maize (40 days of growth)

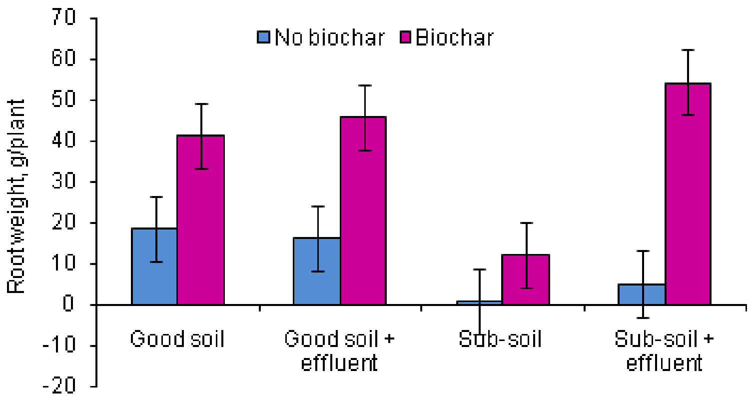


Figure 2. Effect of biochar and effluent added to fertile soil and sub-soil on fresh weight of roots o maize (40 days of growth)

Biochar increased green biomass growth of the maize on the fertile soil in absence or presence of biodigester effluent and in the sub-soil when effluent was applied, but had no effect on sub-soil without effluent (Figure 1). Application of effluent had no effect on green biomass growth in the fertile soil irrespective of the presence or not of biochar. By contrast, the effluent dramatically increased green biomass growth when biochar was applied to the sub-soil but had no effect in the absence of biochar. Effects on growth of the roots mirrored those on the green biomass except in the case of the sub-soil without effluent when the biochar markedly increased root growth (Figure 2).

Soil pH was increased by nearly 2 units due to addition of biochar (Table 1 and Figure 3). There was no effect on soil pH due to application of effluent but values were 0.5 pH units higher on average for the fertile soil compared with the sub-soil.

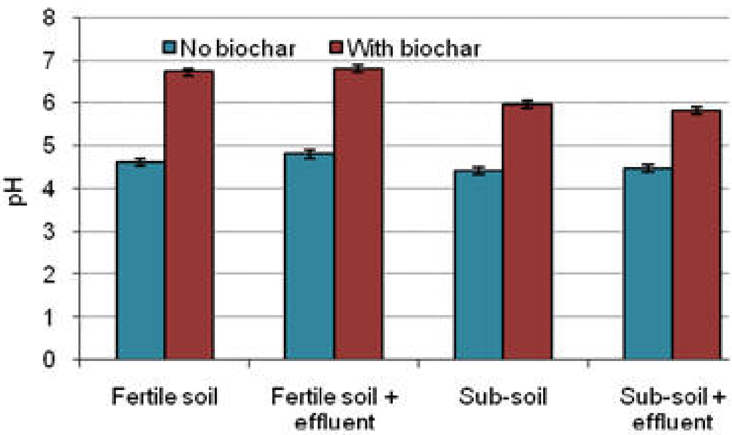


Figure 3. Effect of biochar and effluent on soil pH in fertile soil and sub-soil

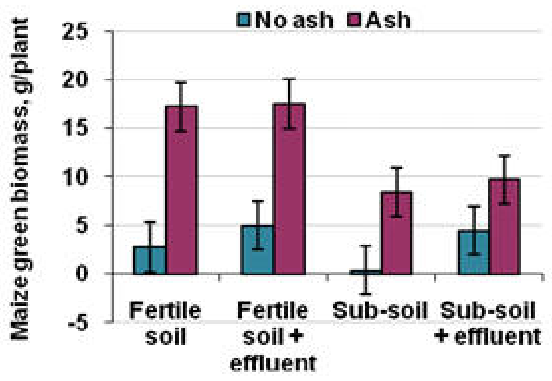
Effects of wood ash

In view of the major increase in soil pH (from 4-4.5 to 6.0-6.5) caused by the addition of biochar, it was hypothesized that one reason for the stimulatory effect of biochar on growth of maize might have been caused by the increase in soil pH.

Experiment 2 was designed to study the effect of ash *per se* in the absence of the carbon which is the other major component of the biochar used in this study. The addition of the wood ash, admittedly at ash levels some 30% higher than when biochar was used, brought about increases in the weight of both the aerial part and roots of the maize but the relative increases were much less than when biochar was used (Table 2; Figures 4 and 5).

Table 2. Mean values for effects of wood ash, effluent and soil type on height and fresh weights of aerial part and roots of maize, and on soil ph (after 40 days growth of the maize)

	Height, cm	Aerial part, g	Roots, g	Soil pH
Wood ash				
With	36.9	10.6	11.5	9.49
Without	22.3	2.89	4.34	4.4
P	0.003	0.001	0.02	0.001
Effluent				
With	29.4	7.40	7.51	6.97
Without	29.8	6.05	8.30	6.92
P	0.92	0.48	0.78	0.25
Soil				
Fertile	39.1	10.6	10.0	6.65
Heavily leached	20.1	2.86	5.84	7.24
P	0.001	0.001	0.16	0.001
SEM	3.1	1.3	2	
P (interactions)				
B*E	0.14	0.005	0.005	0.27
B*S	0.85	0.66	0.66	0.001
E*S	0.04	0.075	0.075	0.166
B*E*S	0.03	0.011	0.095	0.83



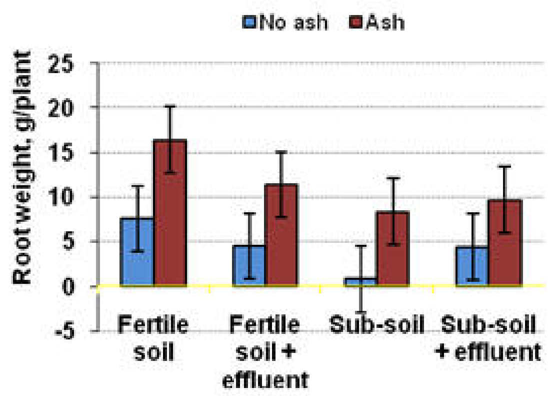


Figure 4. Effect of wood ash and effluent added to fertile soil and sub-soil on fresh weight of aerial part of maize (40 days of growth)

Figure 5. Effect of wood ash and effluent added to fertile soil and sub-soil on fresh weight of the roots of maize (40 days of growth)

Soil pH was raised by 5-6 pH units (Figure 6) to values between 9 and 10. This high degree of alkalinity may have been a deterrent to plant growth.

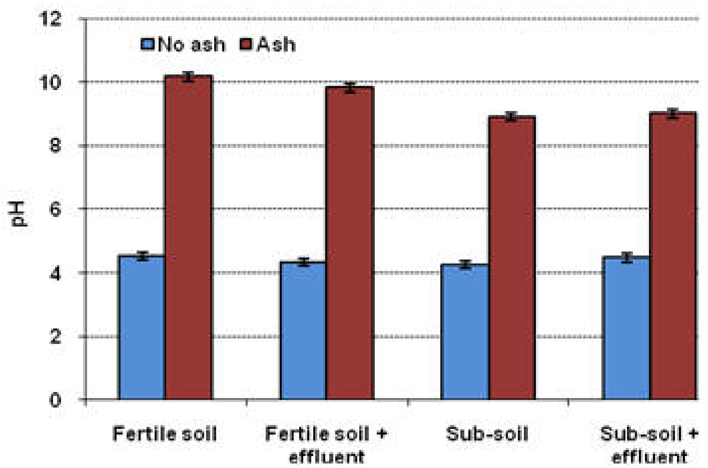


Figure 6. Effect of wood ash and effluent on soil pH in fertile soil and sub-soil

Discussion

The 10% yield of biochar from gasification of sugar cane bagasse is similar to values reported by Miech Phalla and Preston (2005) for Mulberry stems (10.9%), Cassava stems (12.8), Coconut shells (13.7%) and branches from the leguminous tree *Cassia stamea* (10.9%), processed in a similar model of gasifier (Ankur PTY, India).

The increase in growth of the maize brought about by the biochar is in agreement with the majority of reports in the literature (see Sohi et al 2009). Two factors appear to distinguish the biochar used in these studies and that used in most reported experiments. First, the biochar was the product of gasification and therefore would have been submitted to higher temperatures than biochar derived by pyrolysis; and secondly it had a very high content of ash. Such a high ash content (35%) in the biochar used in these studies has not apparently been observed in other experiments. In the research reported by Rondon et al (2007) the biochar was made by pyrolysis of eucalyptus logs and contained only 0.3% of ash. Their data showed an increase in soil pH from 5.0 to 5.4 after applying 40g biochar per 1 kg of soil, much less than the increase from 4.6 to 6.3 in our experiment. The results from using wood ash as soil amendment in Experiment 2 were confounded by the higher level (of ash) that was used and the resulting major increase in soil pH (from 4.4 to 9.5). The much lower growth response of the maize to the wood ash compared with the biochar could be interpreted as the consequence of the absence of the carbon and related organic compounds in the biochar, and/or the negative effect of the excessive alkalinity (soil pH of 9.5) which would have reduced phosphorus availability with formation of insoluble calcium phosphate.

Many researchers have emphasized the importance of nutrient supply, especially nitrogen, as a determinant of plant growth response to soil amendment with biochar (see review by Sohi et al 2009). The significant interaction between application of biodigester effluent and biochar in the sub-soil, but not in the fertile soil, confirms the importance of the relationship between nutrient supply and response to biochar. These findings emphasize the major benefits that biochar combined with biodigester effluent can confer on poor soils with little or no organic matter and low nutrient status (Photos 10 and 11). Similar synergistic effects on plant growth by combining charcoal with chicken manure were observed by Steiner et al (2007).

Photo 10. The sub-soil with no biochar or effluent

Photo 11. The sub-soil after amendment with biochar and effluent

Conclusions

- Biochar produced as a byproduct of the gasification of sun-dried, sugar cane bagasse (the cane stalks were passed two times through a 3-roll mill traditionally employed for making "panela"), contained 35% ash.

- Application of the biochar (50 g/kg of soil) to a fertile soil (from a shaded coffee plantation) increased above ground biomass growth five-fold with no additional benefit from simultaneous application of biodigester effluent. When applied to a sub-soil, there was a synergistic effect of the biochar and the biodigester effluent; the biochar alone increased yield eight-fold but combined with biodigester effluent the increase was twenty-fold. Effects on the root biomass were similar.

- The initial pH of both soils was in the range of 4.0-4.5 and was increased to 6.0-6.5 by addition of the biochar. Effluent application did not affect soil pH.

- Application of ash from a wood-burning stove at 50g/kg soil also increased maize yield but to a level of only one third of that achieved with biochar. The increase in soil pH was double that observed with biochar reaching levels of between 9 and 10.

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Chapter 7. Effect of planting method on biomass yield of New Cocoyam (*Xanthosoma sagittifolium*)

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Abstract

A randomized block design was employed to compare the effect of choice of planting material on the biomass yield of New Cocoyam (*Xanthosoma sagittifolium*). The sources of planting material were suckers taken from the base of the root or sections of the disk taken from the PGF2alpha. There were 4 replications of each treatment arranged in 2 blocks in each of the two locations in the "Finca Ecologica, Santander, Colombia. Plant spacing was 70cm between rows and between plants in the row. Establishment of the plants was experiment was on 15 September 2006. Harvesting of leaves and petioles began on 18 February 2007 and continued at approximately 30 day intervals until 3 October 2007.

Fresh biomass (leaves and petioles) yields were 50% greater when the plants were established from suckers than from disks. The yields from plants established from suckers were equivalent to 128 tonnes/ha/yr fresh biomass, 14.5 tonnes DM and 1.90 tonnes crude protein/ha/year. More leaves were produced from plants established from disks than from suckers but they were much smaller. More suckers were produced by plants established from disks than from suckers, but the overall development of the plants was in favour of those established from suckers. On a DM basis, the leaves accounted for 60% of the biomass and 87% of the crude protein.

Key words: Alocacia, colocacia, disks, leaves, petioles, suckers, taro

Introduction

Research in our laboratory/farm has shown that the foliage from the New Cocoyam (*Xanthosoma sagittifolium*) is one of the most appropriate locally available sources of protein to partially replace soybean meal in diets of growing pigs in Colombia (Rodríguez et al 2006, 2009a,b). Similar conclusions have been made concerning other members of the Araceae family (eg: *Alocasia macrorrhiza* in Vietnam [Pham Sy Tiep et al 2006, 2008; Ngo Huu Toan and Preston 2007; Hoang Nghia Duyet et al 2008]; and *Colocacia esculenta* in Vietnam [Du Thanh Hang and Preston 2008], in Cambodia [Chhay Ty et al 2007, Pheng Buntha et al 2008a] and in Laos [Chittavong Malavanh et al 2008]).

Surveys in Vietnam (Ngo Huu Toan and Preston 2007) and in Cambodia (Pheng Buntha et al 2008b) have shown that it is traditional farmer practice in these countries to use both the leaves and the petioles of different varieties of "Taro" (*Alocacia macrrorhiza and Colocacia esculenta*) as "vegetables" in pig feeding. Surprisingly there appear to be no agronomic studies on any of the species mentioned above.

The objective of the present study was to measure the biomass production of New Cocoyam and to compare two sources of plant material: the 'suckers" derived from the root zone of the plant and "disks" obtained by cutting sections of the corm.

Materials and Methods

Location

The study was carried out in the "Finca Ecológica", TOSOLY, Morario, Guapota, Department of South Santander, Colombia (6° 18" N, 73° 32" W, 1500 msl) between 15 September 2006 and 17 Decedmber 2007. Air temperature ranges between 19 and 28°C in the day, falling to around 12°C during the night. Rainfall is between 2700 and 3000 mm/year and is relatively evenly distributed (Annex 1).

Treatments and design

A randomized block design was employed to compare the effect of choice of planting material on the biomass yield of New Cocoyam (*Xanthosoma sagittifolium*). The sources of planting material were suckers (Photo 1) taken from the base of the root or sections of the disk taken from the corm (Photo 2). There were 4 replications of each treatment arranged in 2 blocks in each of the two locations "A" and "B" (Photos 3 and 4). Planting was on 15 September 2006.

Photo 1. Sucker taken from the base of the root

Photo 2. Disks taken from the corm

Photo 3. Location "A" near bamboo grove

Photo 4. Location "B" 100m distant from Location "A"

Planting and fertilization

Individual plots measured 5.6*3.5m, with 0.7m spacing between plants and 0.7m between rows, equivalent to 22408 plants/ha. The plant material was situated in holes 20cm diameter and 20cm deep (Photos 5 and 6). Loose soil was put at the bottom of the hole at a depth of 5 cm followed by the plant material which was then covered with loose soil to which had been added 300 g poultry manure (from broilers raised in deep litter system). On 12 December 2006, 20 g urea were mixed into the surface of the soil surrounding each plant. A further 20 g urea with 690 g poultry deep litter manure was applied on 14 May 2007.

Photo 5. The holes situated in undisturbed soil

Photo 6. Planting distances were 70cm between plants and between rows

Harvesting

The first harvest was made on 18 February 2007, 156 days after planting and subsequently at intervals ranging from 25 to 35 days until 3 October 2007. All the mature leaves and petioles were removed leaving the two youngest leaves to facilitate the re-growth.

Measurements

The plants harvested from each plot were counted, weighed and separated into leaves and petioles, each of which was weighed separately. DM, crude protein and sugars were determined on representative samples of leaves and petioles from the last harvest. DM was determined by micro-wave radiation (Undersander et al 1993), crude protein according to AOAC (1990) and sugars from the "Brix" readings taken with a hand refractometer.

Statistical analysis

The data were analysed using the GLM option in the ANOVA program of the MINITAB (2000) software. Sources of variation were: Blocks, plant material, harvest date, interaction of plant material*harvest date and error.

Biotest characterization of the soils

The maize "biotest" (Boonchan Chantaprasarn and Preston (2004) was used to assess (i) the relative fertility of the soils from the two locations; and (ii) the response curve to fertilization with poultry litter. In each test a completely randomized design was used with 4 replications of the treatments applied to samples of soil/substrate held in one litre capacity plastic bags (Photo 7a). Three maize seeds were planted in each bag. After germination one or two plants were removed to leave only plant for the growth period of 30 days when the maize plant was harvested (Photo 7b) and the above ground fresh biomass was weighed.

Photo 7a. The plastic bags were placed in holes in the soil

Photo 7b. The maize plants ready for harvesting after 32 days growth

The treatments were:

Test 1

Soils from location "A" and location "B", casts from worms fed with cattle manure (WC), sand and a 50:50 mixture (by fresh weight) of sand and WC. The quantities put in the bags are shown in Table 1. Weights of soil/substrate (g/bag) were 800 for soils from locations A and B, 600 for WC, 1075 for sand and 840 for sand:WC.

Test 2

Levels of poultry litter (g/bag) of 0, 10, 20, 40, 70 and 100 mixed with 800 g soil taken in equal amounts from locations A and B.

In Test 1 the statistical analysis was by the GLM option in the ANOVA program of the Minitab (2000) software. Sources of variation were: treatments and error. In test 2, a polynomial function was applied to the data, the independent variable (X) being the level of poultry litter and the dependent variable (Y) the fresh weight of the maize plant.

Results

Biomass yield of New Cocoyam

Fresh biomass (leaves and petioles) yields over a 255 day period following the first harvest (which was made at 155 days) were 50% greater for New Cocoyam planted from suckers compared with disks (Table 1; Figure 1). These yields are equivalent to 128 and 85 tonnes/ha/yr. With an average DM content of 11.4% and crude protein of 13.1% in DM (Table 2), the predicted yields are 14.5 tonnes DM and 1.9 tonnes crude protein per ha/yr for planting by suckers. Biomass yield increased linearly up to 164 days following the first harvest and then declined, probably reflecting a need for further fertilization.

Table 1. Mean values for fresh biomass yield (kg/plot) at each harvest for New Cocoyam planted by suckers or by disk

Days from planting	Sucker	Disk
155	3.71	1.12
196	6.88	2.76
231	7.58	4.73
261	10.3	6.48
295	18.3	12.3
320	22.4	13.6
351	21.3	14.4
383	19.0	13.9
410	16.7	13.6
Mean	**14.0**	**9.20**
SEM	**0.902**	
Prob.	**0.001**	

Table 2. Mean values for composition of the leaves, petioles and the combined foliage

	Leaf	Petiole	Foliage
Composition, %			
DM	17.0	7.30	11.4
Crude protein in DM,	18.4	4.19	13.1
Sugars in juice	4.0	3.0	
Sugars in DM	19.1	38.1	26.7
Proportions, %			
Fresh biomass	39	61	
DM	60	40	
Crude protein	87	13	
Sugars			

DM, crude protein and sugars were determined on representative samples of leaves and petioles from the last harvest

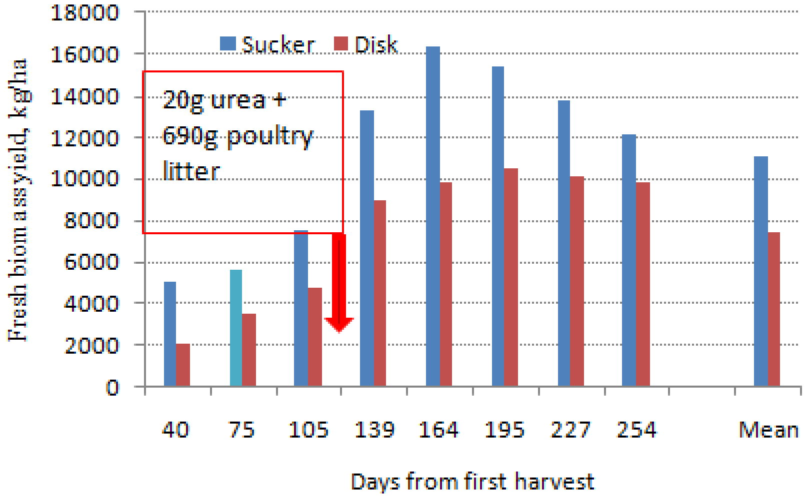

Figure 1. Fresh biomass yields of New Cocoyam planted from suckers or disks, harvested at intervals of from 25 to 34 days

The difference between the biomass yields for each type of planting material decreased linearly with increasing maturity of the plants (Figure 2); however, even at 409 days after planting the yield from plants established from disks was still only 45% of the yield from plants derived from suckers.

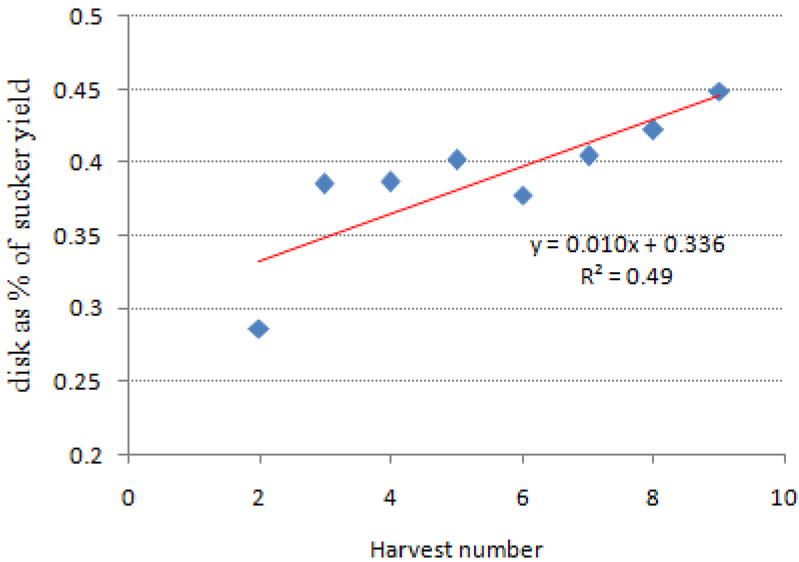

Figure 2. Effect of age of plant on relative yields of New Cocoyam planted from suckers or disks (first harvest not shown)

The proportion of fresh biomass accounted for by the leaves was higher for plants established from disks (Table 3; Figure 3). On a DM basis, the leaves accounted for 60% of the biomass and 87% of the crude protein (Table 2).

Table 3. Mean values at successive harvests for proportion of leaves in biomass (leaves + petioles) from New Cocoyam plants planted as suckers or disks

Days from planting	Sucker	Disk
196	0.371	0.403
231	0.418	0.502
261	0.441	0.444
295	0.373	0.411
320	0.422	0.448
351	0.336	0.356
383	0.331	0.355
410	0.408	0.404
Mean	**0.387**	**0.415**
SEM	**0.011**	
Prob.	**0.001**	

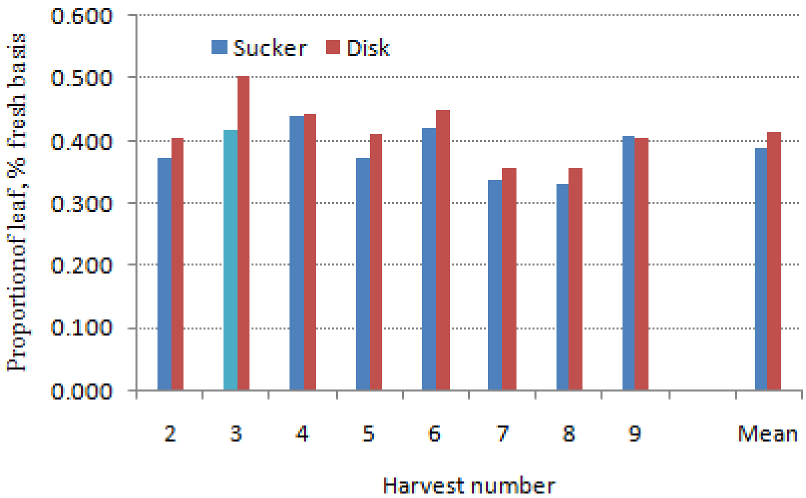

Figure 3. Effect of harvest number on proportion of leaves in harvested biomass from New Cocoyam plants planted as suckers or disks

More suckers were produced by plants established from disks than from suckers, but the overall development of the plants was in favour of those established from suckers (Table 4).

Table 4. Mean values for numbers of suckers and the overall development of the plants (scale 1 to 5 in improved development) for New Cocoyam plants established from suckers or disks

	Sucker	Disk	SEM	Prob.
No suckers	1.00	2.32	0.047	0.001
Development of the plant	4.07	2.12	0.042	0.001

More leaves were produced from plants established from disks than from suckers but they were much smaller (Table 5; Figure 4).

Table 5. Mean values at successive harvests for numbers of leaves per plant of New Cocoyam planted as suckers or disks

	No of leaves/plant		Weight of leaf, g	
From planting,d	**Suckers**	**Disk**	**Suckers**	**Disk**
196	1.70	2.00	32.9	12.6
231	2.01	2.61	35.8	22.6
261	1.83	2.30	60.5	47.0
295	2.95	4.75	54.8	25.9
320	1.87	3.03	108	48.2
351	1.62	2.45	90.3	46.5
383	1.71	2.59	81.5	43.3
410	1.73	2.50	87.8	48.9
Mean	**1.79**	**2.56**	**68.9**	**36.9**
SEM	**0.066**		**3.67**	
Prob	**P=0.001**		**0.001**	

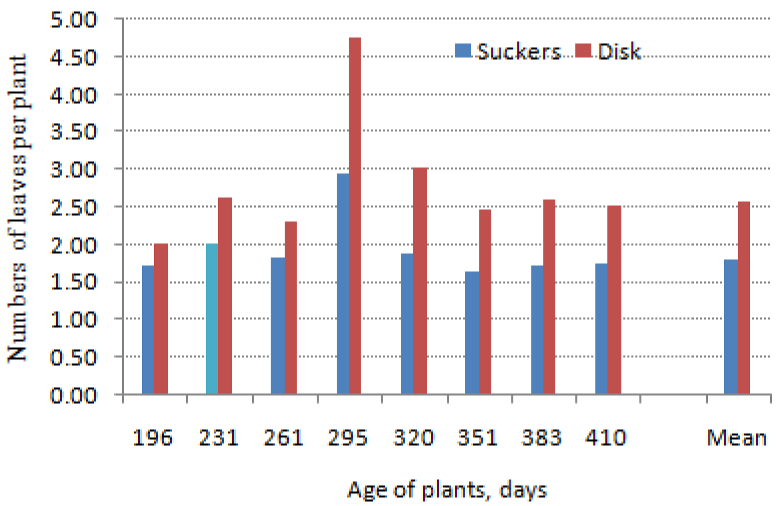

Figure 4 . Effect of harvest number on numbers of leaves in harvested biomass from New Cocoyam plants planted as suckers or disks

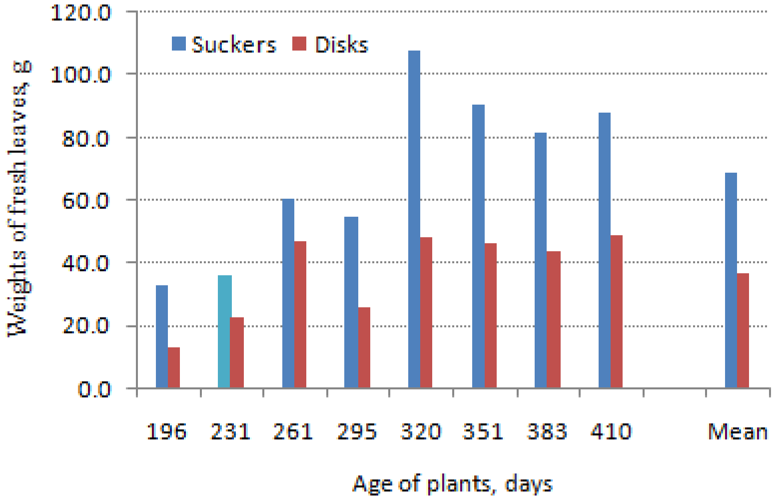

Figure 5. Weights of fresh leaves from New Cocoyam plants established from suckers or disks

Characterization of the soils

As measured by the relative growth of maize the soils from both locations were of inherently low fertility, with no difference in maize yield between the samples of the two soils and sand (Figure 6).

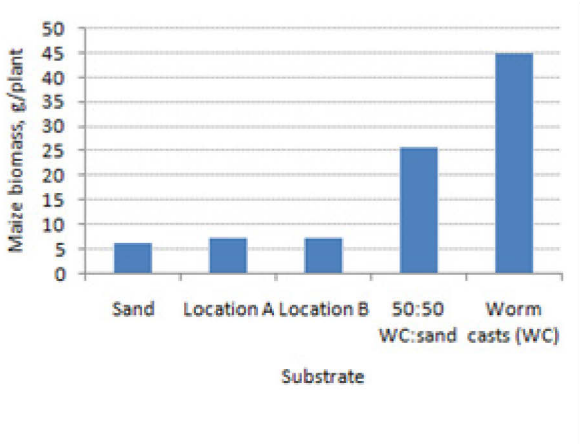

Figure 6. Growth ofmaize in soil taken from the two locations compared with negative (sang) and positive (worm casts) control substrates

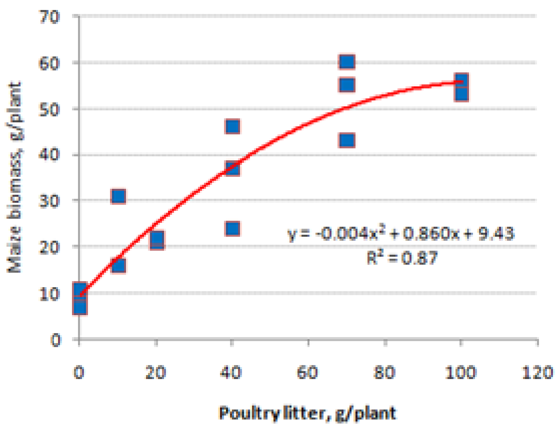

Figure 7. Response in maize growth from adding poultry litter to the soils taken from locations "A" and B

Discussion

The biomass DM and crude protein yields of the New Cocoyam in the present study are encouraging taking account of the low inherent fertility of the soils in which the plants were grown. The fertilization procedure can be criticized in that the quantities applied were large and given in only two applications (equivalent to 97 kg N/ha at planting and a further 410 kg N/ha 280 days after planting) over the overall growing period of some 500 days. The peak in the yield per harvest some 50 days after the final application of fertilizer and the subsequent decline in yield, are indicative of the need for fertilizer and for this to be applied more frequently.

The comparative results from the two planting methods indicate the possible strategy to be followed in establishing plantations of New Cocoyam. If established plants are available it is obviously better to take the suckers from these plants for the new plantings. However, in situations where these are not available, a "nursery"could be prepared in which the plants would be established from disks. As each disk produces up to 3 suckers, these could then form the basis for the commercial plantation.

From observations, and the recorded pattern of biomass yields, it is clear that New Cocoyam responds to fertilization with nitrogen. Subsequent experiments should be directed to measuring biomass yield responses to increasing levels of fertilization from biodigester effluent. The results of the "biotest" (Figure 7) showed a good response in growth of maize on the test soils to applications of poultry litter at N equivalent rates of 20 kg/ha over the 32 day growth period, equivalent to about 250 kg N/ha/year. This annual quantity of N, divided into applications at one or two month intervals, could be taken as a reference point for future agronomic studies with New Cocoyam for forage.

The harvest interval of about 30 days applied in this study also merits closer study. We have observed that shorter intervals may be more appropriate especially in periods when the rainfall is more intense.

Conclusions

- Fresh biomass (leaves and petioles) yields of New Cocoyam were 50% greater when established from suckers than from disks.
- The yields from plants established from suckers are equivalent to 128 tonnes/ha/yr fresh biomass, and 14.5 tonnes DM and 1.8 tonnes crude protein/ha/year.
- On a DM basis, the leaves accounted for 60% of the biomass and 87% of the crude protein

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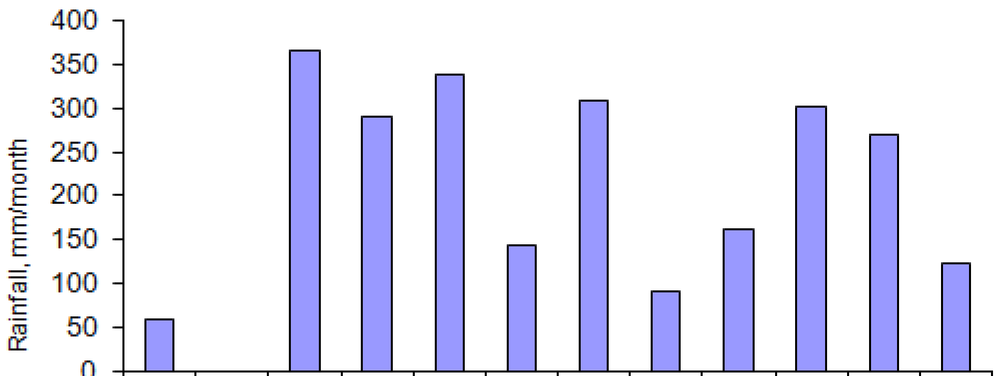

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2007	60	0	366	290	338	144	309	91	162	302	270	123

Annex figure. Monthly rainfall in TOSOLY farm during 2007

Chapter 8. A note on ensiling the foliage of New Cocoyam (*Xanthosoma sagittifolium*)

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Abstract

Complete leaves and petioles of New Cocoyam (*Xanthosoma sagittifolium*) were harvested from 40 plants grown in the TOSOLY farm in Santander province, Colombia. Ten plants were separated into leaves and stems, which were weighed and then each chopped finely with a knife to give representative samples of leaves and petioles, which were taken for analysis for DM, N and ash. The other 30 plants were macerated in an ensiling machine and the macerated product thoroughly mixed and enclosed in 28 air-tight plastic containers of 200ml capacity. Four samples were allocated for analysis on each of days 0 (before ensiling), 1, 2, 3, 4, 5 and 7 days later. The containers were kept at ambient temperature in an enclosed room.

DM and crude protein contents of fresh petiole (7.3 and 5.2) were much lower than in the fresh leaf (17 and 18% in DM, but sugars were higher (38 and 20% in DM). On a fresh basis, there was twice as much biomass in the petiole than in the leaf, but these proportions were reversed in terms of DM. The pH fell from 5.81 in the fresh mixture of leaf+petiole to 4.37 within 24h, and to 3.98 in 48h. Lactic acid was 2.07% in DM.

Key words: Crude protein, lactic acid, pH, pigs

Introduction

Early research on determining the nutritive value for pigs of the foliage of New Cocoyam (*Xanthosoma sagittifolium*) was based on feeding the fresh leaves (Rodriguez et al 2007, 2009a,b), This is not very convenient under practical farm conditions as regular daily supplies are not always available and often the foliage is not harvested at the most appropriate physiological6he next step was to ensile the leaves so that the harvest stage could be optimized and also to ensure a regular supply of the leaves for feeding to the pigs. To facilitate the fermentation, 10% fresh sugar cane juice (20% sugars) was added to the leaves. This was effective, but time-consuming to ensure thorough mixing of the juice with the leaves (Rodríguez Lylian 2007, unpublished observations). There was also the question of what do with the petioles, as harvesting only the leaves is not appropriate for the plant growth cycle; also transporting the leaves alone was not practicable by the traditional system of loading them on the horse; by contrast it was easy to load the leaf and petiole together (Photo1).

Photo 1. New Cocoyam leaves + petioles transported by "Mariscal" in TOSOLY farm

Ensiling the chopped petioles was then tested, with the idea that they could be part of the diet of pregnant sows. Despite the high moisture content (over 90%) the process of ensiling proved to be easy, with the pH falling to below 4.5 within 24 h (Rodríguez Lylian 2007, unpublished observations). Expressing the juice from the fresh petiole and measuring the brix by refractometer indicated a sugar content in the juice of 3, equivalent to approximately 38% of sugar in the DM.

On the basis of these observations and the practical daily work in TOSOLY farm it was hypothesized that the petiole could serve as a useful additive for facilitating the ensiling of the leaves of New Cocoyam and other forages.

Materials and Methods

Location

The study was carried out in the "Finca Ecológica", TOSOLY, Morario, Guapota, Department of South Santander, Colombia (6° 18" N, 73° 32" W, 1500 masl) between 1 and 14 August 2009. At that time the air temperature ranged between 19 and 28°C in the day, falling to around 12°C during the night.

Experimental design

Complete leaves and petioles of New Cocoyam were harvested from 40 plants. Ten plants were separated into leaves and stems, which were weighed and then each chopped finely with a knife to give representative samples for analysis of leaves and petioles for analysis of DM, N and ash. The other 30 plants were macerated in an ensiling machine (Tormetal, Funza, driven by 3KW electric motor at 3500 rpm). The macerated product was thoroughly mixed and enclosed in 28 air-tight plastic containers of 200ml capacity. Four containers were assigned for analysis on each of days 0 (before ensiling), 1, 2, 3, 4, 5 and 7 days later. The containers were kept at ambient temperature in an enclosed room.

Measurements

pH was measured with a digital electrode (Pocket sized pH meter - HANNA) immediately after opening the containers. The contents were then dried by micro-wave radiation (Undersander et al 1993). Samples of the dried material were analyzed for DM, crude protein, ash and lactic acid by AOAC (1990) procedures. The descriptive statistics option in the Minitab (2000) software was used to derive mean values and standard deviations of the pH values of the New Coocoyam silage.

Photo 2. Mixed New Cocoyam leaves + petioles ensiled in 200 ml containers

Results and discussion

Composition of New Cocoyam leaves and petioles

DM and crude protein contents of petiole were much lower than in the leaf but sugars were higher (Table 1). On a fresh basis, there was twice as much biomass in the petiole than in the leaf, but these proportions were reversed in terms of DM.

Table 1. Composition of foliage of New Cocoyam

	Leaf	Petiole	Total
DM	17	7.3	13.1
DM basis, %			
CP	18	5.2	12.9
Ash	8.96	12.9	10.5
Brix	4	3	
Sugars	19.5	38.1	27.0
Proportions, %			
Fresh	39	61	
Dry	60	40	

Effect of ensiling

The pH fell from 5.81 in the fresh mixture of leaf+petiole to 4.37 within 24h, and to 3.98 in 48h, subsequently remaining below 4.0 though the rest of the ensiling period (Figure 1). The rapid fall in pH is indicative of conditions, under which the breakdown of the protein can be expected to be minimized (McDonald 1981). The levels of DM and of lactic acid were lower (Table 2) than what are considered to be preferred levels (>25% and >6.0%, respectively, for well-preserved silage) (McDonald 1981). However, other attributes such as smell and colour were normal, with excellent acceptability by pigs, ducks and hens. There was no mould development. The process has been applied successfully in the TOSOLY farm with over 40 tonnes of New Cocoyam silage being made over the past 30 months.

Table 2. Mean values for composition of New Cocoyam foliage (combined leaves and petioles) after 7 days of ensiling

pH	3.95
DM, %	12.6
Crude protein, % in DM	14.4
Lactic acid, % in DM	2.07

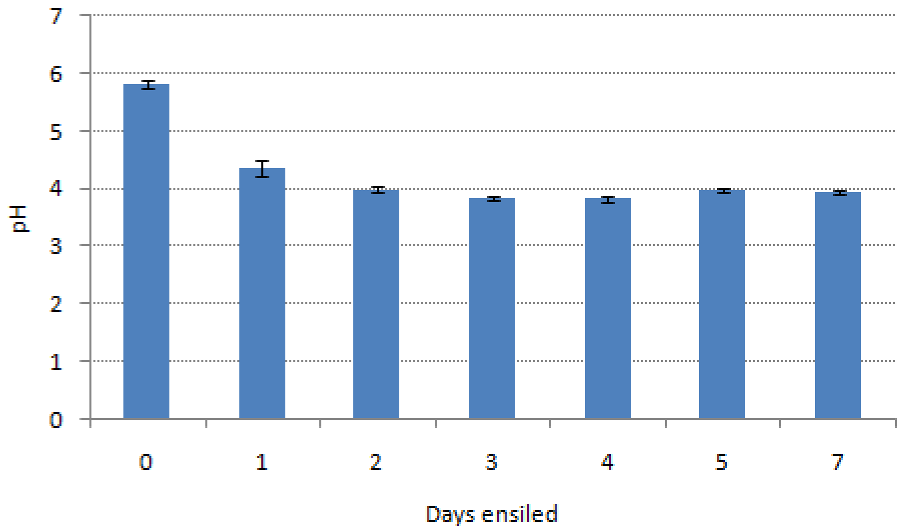

Figure 1. Mean values (with SD) of pH of mixed leaf+petiole of New Cocoyam, before and at 1, 2, 3, 4, 5 and 7 days after ensiling

Acceptability of the technique by people is also important and has been very positive as the ensiling of the intact leaves + petioles is much easier than the process of ensiling only leaves. To ensile leaves + petioles requires passing the intact foliage through the ensiling machine such that the final product goes directly into the plastic container. By contrast, to ensile only the leaves it was necessary to spread them on the floor to be mixed with the sugar cane juice, the mixture then being packed into the plastic container (Photos 3, 4, 5, 6, 7 and 8).

Photo 3. Ensiling New Cocoyam leaves (mixing with Sugar cane juice at 10 % in fresh basis)

Photo 4. Ensiled New Cocoyam leaves

Photo 5. New Cocoyam separated into petiole and leaves prior to each being macerated in the ensiling machine.

Photo 6. Petiole ensiled directly in a plastic container.

Photo 7. New Cocoyam leaves and petiole being introduced into the ensiling machine and directly from the machine into the plastic container

Photo 8. Macerated leaves + petioles delivered directly from the machine into the plastic container

Conclusions

- Mixed leaves and petioles of New Cocoyam, in the proportions that occur naturally in the plant, can be ensiled successfully without the need for additives.
- The process has been applied successfully with over 40 tonnes of New Cocoyam silage made in the TOSOLY farm over the past 30 months. Acceptability by pigs, ducks and hens has been excellent.
- The ensiling process is a fundamental feature of the appropriate management of the New Cocoyam crop, as well as ensuring a permanent supply of silage for the pigs.

Acknowledgments

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Chapter 9. Gasification of fibrous crop residues and livestock production; essential elements in establishing carbon-negative farming systems

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Abstract

The feedstocks used in a down-draft gasifier were sugar cane bagasse and mixed stems of Mulberry (*Morus alba*) and Tithonia (*Tithonia diversifolia*). The tests were done under commercial conditions over an extended period (90 days) on a farm in Colombia. The bagasse was the byproduct of the extraction of the juice from sugar cane stalks, which was fed to pigs; the stems were the residues after the leaves and (in the case of the Mulberry) the rind had been consumed by confined goats The 10KW gasifier (Ankur WBG10) was imported from India.

Rates of consumption of the feedstock were similar for the bagasse and the stems (4.32 and 4.65 kg DM/h). The stems produced a greater percentage of biochar (11.7% of the DM in the feedstock) than the bagasse (8.5%). Management of the gasifier was simpler in the case of the stems as these flowed more easily in the hopper, whereas the bagasse tended to "bridge" requiring frequent agitation to maintain the gas flow. It was estimated that the bagasse from the 1.5ha of sugar cane required to feed a constant population of 45 pigs (about 50 kg DM daily), and the 1ha in forage trees for 20 breeding goats, could provide electrical energy yields of 50 KWh daily. The biochar residue (35% ash; 65% carbon) from the gasification of the bagasse and tree stems (2.5 ha) would be sufficient to condition 0.1 ha of crop land annually with the potential to sequester annually up to 5.4 tonnes of carbon dioxide.

Key words: Bagasse, electricity, mulberry, renewable energy, residues, sugar cane, Tithonia diversifolia

Introduction

The three components of the world crises – economic recession, global warming and resource depletion (especially fossil fuels) - presently facing humanity are closely inter-related. The gaseous emissions from the burning of fossil fuels are the major contributor to global warming; the apparently inexhaustible supply of fossil fuels facilitated the exponential growth of the world population during the past century and, more recently, the unsustainable indebtedness in the developed countries, which led to the present economic recession.

In the past century, the needs for energy, and indirectly for food, of the expanding world population were provided by cheap oil. The inevitable process of adaptation to increasing cost and declining supplies of oil, will almost certainly change the future life style of the majority of the world's population.

For the future, the only long term alternative to fossil fuel (as exo-somatic energy, that is energy not derived from digested food – muscle power) is solar energy, utilized either directly as a source of heat, or indirectly in solar-voltaic panels, as wind, movements of waves and tides, or in biomass produced by photosynthesis. Solar energy will also have to be relied on to produce food, in what must surely have to be rural small-farm systems, to support the largely urbanized population.

The green revolution which dramatically increased food supplies during the last 40 years was a "fossil energy " revolution as it was energy in the form of oil and natural gas which facilitated production of fertilizers, especially nitrogen, pesticides and herbicides, and the mechanization and irrigation that permitted multiple cropping. Another "energy" revolution is possible but it will be based on making greater use of the energy derived daily from the sun. It must also produce both energy and food and have an EROEI (Energy Returned On Energy Invested) of at least 5 (Hall et al 2008a,b). It will also need the support of human energy and increased numbers of people working in rural areas.

There are few difficult decisions about producing food by photosynthesis. By contrast, the ideas proposed for redirecting energy from the sun into potential energy to replace that of fossil fuels are many. The alternatives that are currently practiced commercially (although in most cases with a high degree of Government subsidy) can be divided into processes that depend on (i) the products of photosynthesis (eg:: ethanol produced by fermentation of sugars derived from cereal grains, cassava roots and sugar cane; and biodiesel from soya beans, rapeseed and oil palm); or (ii) that use the physical qualities of solar energy directly (photovoltaic panels, solar water heaters, windmills and tidal barrages).

Surprisingly, gasification which is a proven technology for using biomass as a source of fuel, and which was applied widely in several "oil-dependent" countries during World War II, has received little attention from policy makers and the media. Yet, as will be shown in this paper, it appears to hold real prospects of being especially applicable at the small, dispersed farm level.

Gasification is a process for deriving a combustible gas by burning fibrous biomass in a restricted current of air. The process is a combination of partial oxidation of the biomass with the production of carbon which at a high temperature (600-800 C) acts as a reducing agent to break down water and carbon dioxide (from the air) to hydrogen and carbon monoxide, both of which are combustible gases. The advantages of gasification are that: the feedstock is the fibrous parts of plants which are not viable sources of food; the energy used to drive the process is derived from the combustion of the feedstock; there is minimal input of fossil fuel (mainly for the construction of the gasifier and associated machinery); the process can be de-centralized as units can be constructed with capacities between 4 and 500KW.

Fuel energy as a byproduct of livestock production

Miech Phalla and Preston (2005) reported data in Cambodia for a down-draft gasifier imported from India (Ankur Scientific Energy Technology Pvt. Ltd; http://www.ankurscientific.com). The gasifier unit (Model WBG15) was connected to a 25HP gas engine coupled with a 15KVA alternator (Photo 1).

Photo 1. The gasifier, engine and alternator setup in Cambodia

Miech Phalla and Preston (2005) compared four feedstocks: the woody stems from cassava and mulberry, the branches from an ornamental tree and the husks from coconut (Photos 2-5).

They measured various criteria (Table 1) of the gasification process with the engine-alternator operated with a constant load of 9KW (the electrical power needs of the CelAgrid experimental farm where the tests were carried out).

Photo 2: Chopped dried stems of cassava

Photo 3: Chopped dried stems of mulberry

Photo 4: Chopped dried stems of *Cassia stamea*

Photo 5: Chopped husks of coconut

Conversion rates of dry feedstock to electricity were similar for all 4 feed stocks despite the wide range in bulk density (Table 1).

Table 1: Mean values for gasifier characteristics using coconut shells-husks, cassava stems, mulberry stems and branches of Cassia stamea as feedstock

	Cassia	Cassava	Mulberry	Coconut	SEM	Prob.
Biomass, kg						
Initial	36.7	32.3	33.7	34.4	1.3	0.21
Final	4.93	1.9	0	3.07	2.19	0.49
Consumption	36.9	35.1	40	36.4	2.9	0.69
Moisture, %	14	13.3	15.7	14	1.4	0.69
Density, g/litre	348a	97.0c	273b	128c	10.4	0.001
Duration, h	3.91	3.67	4.09	4.02	0.328	0.81
Output, kwh	27.4	25.7	28.7	28.2	2.29	0.81
Conversion#	1.23	1.18	1.18	1.11	0.044	0.42
Efficiency##	0.187	0.204	0.204	0.217	0.0082	0.17
Biochar, g/kg biomass DM	109	128	109	137	16.5	0.58

 # kg dry biomass/kwh; ## Assumes 15 MJ/kg biomass DM and 3.6 MJ/kwh of electricity

abc Means in the same row without common letter are different at P<0.95

Three problems associated with use of biomass as fuel are: (i) its low density (eg: from 97 to 350 kg/m^3; Table 1), resulting in high costs of transport if processed in a centralized utility (as with increasing distance, fossil fuel rather than animal or human power is needed); (ii) the cost when it is the sole product of the cropping system; and (iii) the potential conflict if land presently devoted to food crops is diverted to production of biomass for fuel. These problems do not arise if the biomass is used at the point of production and it is the byproduct of crops that are grown primarily for human food or animal feed.

Hypothesis

The hypothesis underlying the present study is that the bagasse, derived form sugar cane stalks passed two times through a 3-roll crusher (known in Colombia as *a trapiche.* Photo 6), and stems of forage trees remaining after the leaves were consumed by goats, could be satisfactory sources of feedstock in a down-draft gasifier, designed originally to be fueled with wood chips.

Photo 6. The three-roll crusher used to extract the juice from stalks of sugar cane

Materials and methods

Location

The study was done in the farm “TOSOLY" , located at 1500 masl in the Santander department of Colombia, approximately 250 km north of the capital Bogotá.

The gasifier

A 10KW down-draft gasifier (Model WBG-10) (Photo 7) was imported from Ankur Scientific Energy Technology Pvt. Ltd, in India. It was connected to a Dipco diesel engine modified to operate in 100% producer gas mode with a 230v, 3-phase alternator to give gross output of about 9 kWe (with a net output of 8 kWe and a continuous output of 7 kWe).

Photo 7. The "Ankur" gasifier inTOSOLY farm

The whole system comprises three main units:

- Gasifier
- Filter system
- Engine and alternator

The basic features of the system are (according to the direction of the gas flow):

- **Gasifier** divided into 3 sections: hopper, reaction unit and ash collector. The hopper stores the feedstock (capacity about 100 litres). It consists of *drying zone* and *pyrolysis zone.* The reaction zone has a *combustion zone* and *reduction zone*. The ash section is the bottom part for storing ash and char (biochar).
- **Venturi scrubber** is a device for drawing the air into the gasifier system using a current of water driven by a small pump.
- **Cyclone separator** is the place for cooling, cleaning and separating the gas from the water
- **Fine filter** is a container, filled with saw dusk for capturing dust.
- **Safety filter** is a container with cloth 1x1 mm mesh sieve.

The gas emerging from these filters is extremely pure and clean, suitable for burning in an internal combustible engine.

- **Flare** is a tube in a vertical plane for testing the gas quality by burning before the engine starts
- **Gas control valve** determines the amount of gas going into the engine according to the needs of the engine
- **Air filter** for cleaning air and mixing with the gas prior to entering the ignition zone of the engine
- **Engine** 10 HP DIPSO gas engine drives a 5 KVA generator for electricity
- **Exhaust pipe** is hot (about 250◦C) and used for drying wet feedstock.

The farming system

The farm (Figure 1) extends to 7 ha of which 1.22 ha are in natural forest, 1.44 ha in Arabica coffee grown under shade from "Guamo" (*Inga hayesii* Benth) trees, 1.5 ha in sugar cane, 0.50 ha in permanent plantations of forage trees (mainly Mulberry [*Morus alba*] and Tithonia [*Tithonia diversifolia*] and 0.30 ha in New Cocoyam (*Xanthosoma Sagittifolium*). The remaining 2 ha are accounted for by areas under citrus, bamboo (Guadua), pasture, fish ponds, roads and buildings.

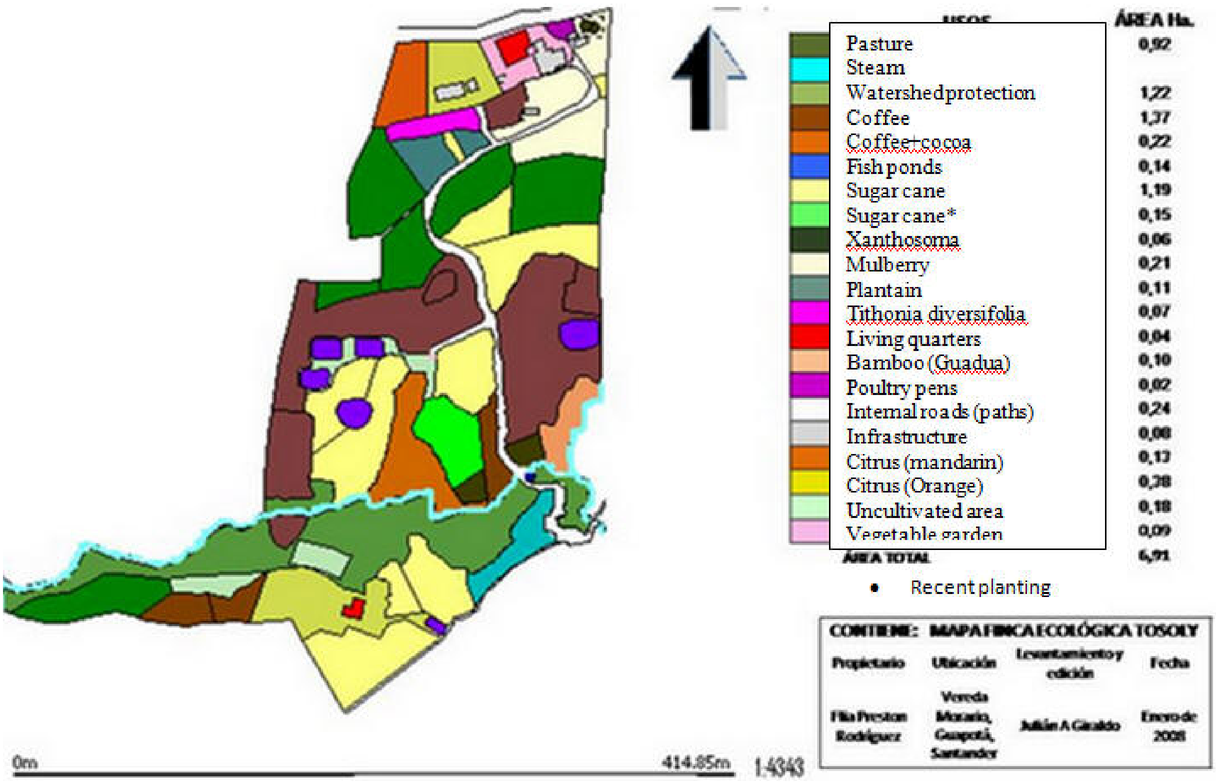

Figure 1. Map of the TOSOLY farm

For the purposes of this study the components of the farm devoted to combined feed and fuel production were sugar cane and the forage trees (Figure 2).

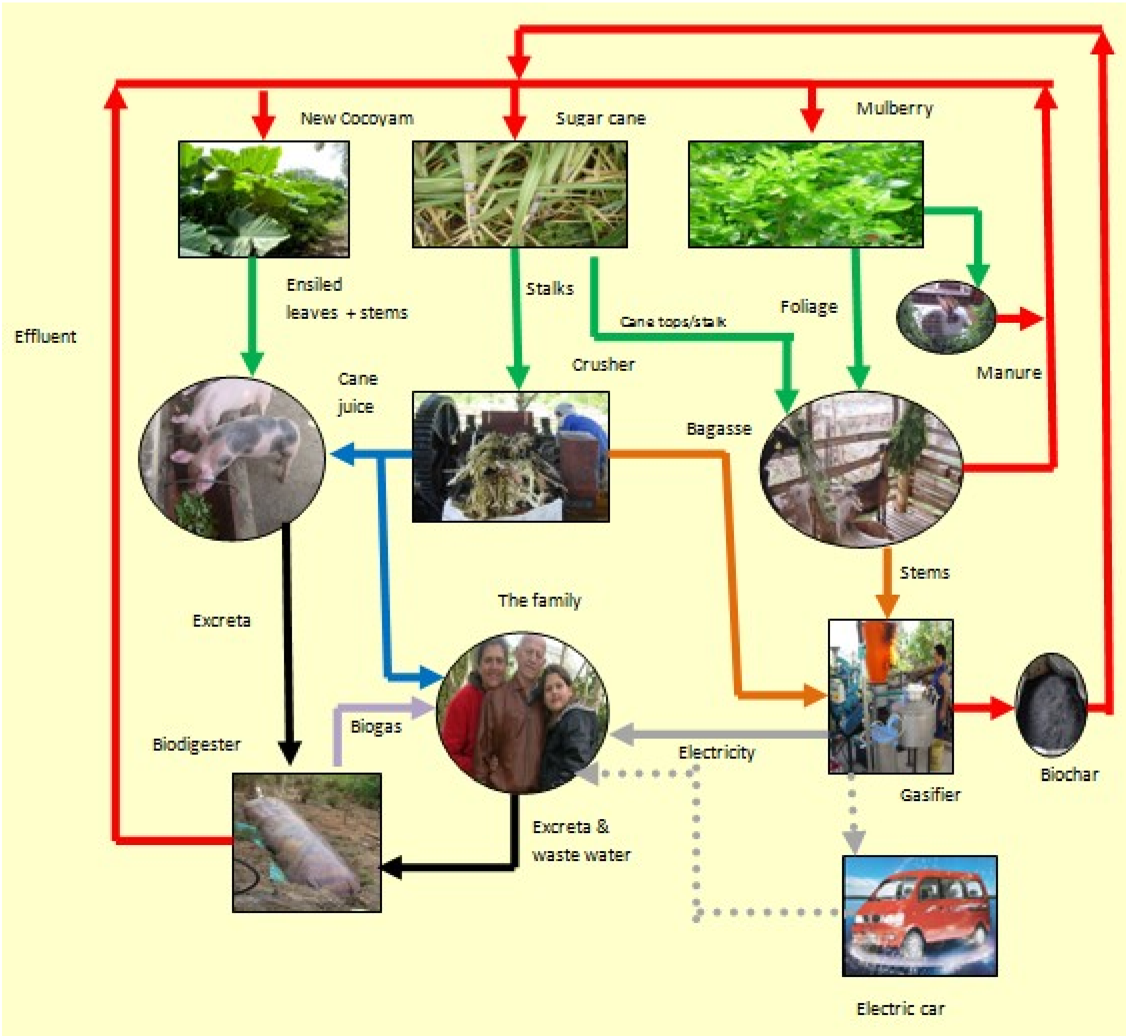

Figure 2. Flow diagram of the principal activities in the TOSOLY farm

Experimental design

This consisted of extended periods operating the gasifier, first with dried sugar cane bagasse (74 days) and then with the chopped mixed stems from the forage trees (16 days).

Sources of biomass

The whole sugar cane plant was harvested and the tops (leaves + growing point) separated from the stalk, which was then passed twice through a 3-roll mill (*trapiche*) (Photo 6). The extracted juice was the dietary energy source for the pigs (n=40 fatteners; 5 sows); the " tops" were chopped prior to feeding them as the energy source for the goats and cattle. The bagasse (the fibrous residue after juice extraction) represented about 35% of the fresh weight of the cane stalk and contained from 55 to 65% moisture. It was sun-dried during 1 to 2 days to a moisture content of about 15%. The large pieces were then separated and used as litter for the goats and cattle; the remaining smaller particles (1 to 3 cm) were stored for use as fuel in the gasifier (Photo 8).

Photo 8. Fine bagasse on the left for the gasifier; coarse particles are used as litter for goats and cattle but could be chopped and used in the gasifier

Foliage from the Mulberry and Tithonia trees was harvested at 6 to 8 week intervals, removing all the fresh biomass after cutting about 50 cm above soil level. The mixed foliages were fed immediately to the goats, that preferentially selected the Mulberry of which they ate the leaves and the rind which they stripped completely from the stems (Photo 9).

Photo 9. Mulberry foliage on the left (most of the rind on the stems has been eaten); Tithonia on the right

For the Tithonia only the leaves were eaten; the stems were left with the rind untouched (Photo 11). The stems of both trees that were not eaten by the goats (Photo 10) were collected, passed through a high speed (3500rpm) chopper (driven by a 3KW electric motor which received power from the gasifier-alternator) and sun-dried to15% moisture for later use in the gasifier.

Photo 10. Residual stems left by the goats; the white stems (without the rind) are from the Mulberry; the green ones with leaves attached are from the Tithonia

Measurements

Records were kept daily of the quantities of feedstock put into the gaifier, the operating time, and the amounts of residual biochar. The moisture content of the feedstocks was recorded with an electronic meter. .

Results

The gasifier was operated many more days on sugar cane bagasse than on tree stems (Table 3), reflecting the relative availabilities of the two sources of feedstock. On the days when tree stems were the source of feedstock, the gasifier was operated for longer periods, in this case reflecting the reduced maintenance (frequency of agitating the feedstock in the hopper) as the stems "flowed" more easily downwards to the combustion zone. Rates of consumption of the feedstock were similar for the bagasse and the stems.

The stems produced a greater percentage of biochar (11.7% of the DM in the feedstock) than the bagasse (8.5%). Estimates of the potential output of electrical energy assumed the alternator was always running on full load which was not the case, as the load depended on the capacity of the lights/motors that were in use when the gasifier was operating. An assumed conversion rate of 1.2 kg feedstock DM/KWh was applied on the basis of the data recorded by Miech Phalla and Preston (2005), who operated the gasifier system under conditions of a constant full load during the time their tests were made.

Table 2. Mean values for rate of use of feedstock and production of biochar in a 10KW down-draft gasifier charged with sugar cane bagasse or mixed stems of Mulberry and Tithonia trees

	Bagasse	**Stems**
Operating time		
Number of days	74	16
Hours per day	3.73	5.70
Feedstock, kg		
Air-dry/d	19.0	31.2
DM/d	16.1	26.5
DM /h	4.32	4.65
Feedstock		
DM, %	15	15
Density, g/litre	52	96.8
Ash, % in DM	1.65	1.80
Biochar		
kg/d	1.37	3.10
% of feedstock DM	8.48	11.7
Ash content, %	28.9	34.8
Engine/alternator		
Hours/day	3.73	5.70
DM/h, kg	4.32	4.65
KWh/d#	13.4	22.1

 # Potential output on full load using the conversion factor of 1.2 kg DM/KWh (Miech Phalla and Preston 2005)

Discussion

The objective of this experiment was to derive data and personal experience from the long term (90 days) operation of a down-draft gasifier using sugar cane bagasse and stems of forage trees as the feedstock. No major problems were encountered other than the need to periodically agitate the contents of the fuel hopper when bagasse was the feedstock. This inconvenience could be overcome by changing the design of the feed hopper, so the sides were vertical and not shaped like a cone. Fitting a screw augur that would progressively push the feedstock down to the combustion zone is another possibility. The final output of such a system is of course the quantity of electric power that is generated. This could not be measured as no meter was available. In any event, as discussed earlier, the KWh output is a function of the load imposed on the alternator, and under the practical circumstances of the present study, this was highly variable. Future plans are to install a battery bank of 110v which will be charged by the alternator, thus allowing it to be run at close to maximum efficiency when the conversion rate should be similar to that observed by Miech Phalla and Preston (2005; Table 1).

A broadly similar biomass gasifier system, designed to produce a combustible gas from sugar cane trash (the dead leaves which fall from the plant during growth plus those removed from the stalk when it is harvested) and sugar factory bagasse was described by Jorapur and Rajvanshi (1997). The construction differed from the Ankur gasifier in that the hopper had parallel sides (Photo 11; Figure 3) and no throat, which facilitated downward movement of the low density feedstock. As the gas produced was used in a furnace there was no need to cool or clean it. In discussions with the designer (T R Preston, personal communication) it was apparent that the system was designed only for thermal applications, and that the gas was not of suitable quality for use in an internal combustion engine. There were other differences compared with the Ankur system in that the yield of biochar was much higher (24% of weight of dry feedstock) although the ash content was similar (35-40%).

Photo 11. The downdraft, open top, throatless gasifier desiigned to produce a combustible gas from sugar cane trash (dead leaves) and sugar factory bagasse (Source: Jorapur and Rajvanshi 1997)

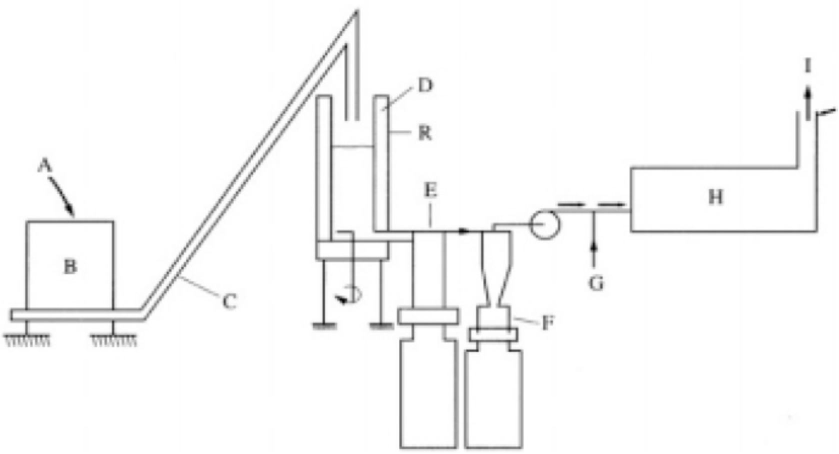

Figure 3 Schematic diagram of sugarcane leaf-bagasse gasification system: A biomass from storage piles, B hopper, C conveyer, D refractory walls, E char collector, F cyclone, G air, H furnace, I chimney, R reactor

The normal consumption of electricity on the farm is of the order of 5 to 10 KWh daily which assuming the conversion rate of 1.2 kg dry feedstock/KWh, would require from 6 to 12 kg dry feedstock daily. The daily consumption of sugar cane juice for the pig unit (n=40 fatteners and 5 sows) is of the order of 225 litres daily which requires the crushing of 350 kg of cane stalks daily, which is 128 tonnes annually. With an annual yield of 80 tonnes stalks/ha the required cane area is1.6ha. The daily production of bagasse is therefore of the order of 50 kg (DM basis) sufficient to produce about 41 KWh of electricity daily, which would provide a surplus of the order of 35KWh daily that could be fed into the regional electricity grid or used directly for activities in the immediate community such as (in the future!) the charging of the batteries of electric vehicles. In addition there is the potential supply of electricity from the tree stems which is estimated to be of the order of 11 KWh day when the area planted with forage trees reaches the planned 1 ha.

Biochar has been shown to be an excellent conditioner for the acid soils that predominate in the farm (Rodríguez et al 2009) and generally in tropical latitudes. It is also expected that most of the carbon in the biochar will be permanently sequestered when incorporated in the soil (Lehmann 2007). From the 50 kg of bagasse DM derived daily from 330 kg/day of sugar cane stalks, plus the 14 kg of DM as tree stems, the daily production of biochar will be about 6 kg (=2.19 tonnes/year) of which 4 kg will be carbon. In one year this is 1460 kg of carbon (5.35 tonnes of CO_2) sequestered annually. The 2.19 tonnes of biochar per year (from 2.5 ha) is sufficient to fertilize 0.1 ha of crop area, assuming an application rate of 20 tonnes/ha (Lylian Rodriguez and T R Preston, Unpublished data). The benefits in terms of reduced fertilizer needs have yet to be quantified but appear to be considerable (see Rodriguez et al 2009).

Conclusions

- Production of electricity from sugar cane bagasse and stems of forage trees (in a small-sale farming system as described in this paper) is commercially feasible, with potential electrical energy yields of 50 KWh daily derived from (i) the sugar cane required to provide the energy needs of a continuous pig population of 40 fatteners and 5 sows (1.5ha in sugar cane with annual yield of 80 tonnes/ha) and (ii) the forage trees (1 ha) fed to goats (n=20).
- The byproduct of this process – biochar – will be sufficient to condition 0.1 ha of crop land annually with the potential to sequester annually up to 5.4 tonnes of carbon dioxide from the 1.5 ha of sugar cane and 1 ha of forage trees.
- Other benefits of the live stock component of this integrated farming system, not quantified in this paper, are the production of biogas from the recycled pig manure, and the fertilizer value of the biodigester effluent and the manure from the goats.
- Integrating live stock with energy production creates synergies which will be lost if each activity is pursued independently.

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Chapter 10. Energy returned on energy invested (EROEI); the case for gasification as a component of an integrated live stock based farming system

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Abstract

The aim of the present study was to measure the Energy Return on Energy Invested (EROEI) in an integrated farming system in which: (i) fibrous crop byproducts (sugar cane bagasse and stems from forage trees) are used as feedstock to produce " producer" gas in a down-draft gasifier; and (ii) all high moisture organic wastes from pigs and the farm family are fed into a biodigester to produce biogas. The hypothesis was that the production of a combustible gas from biomass (gasification), when conducted as part of an integrated farming system involving live stock, would have a much higher EROEI, and be more environmentally friendly, than the production of other biofuels, especially ethanol production from maize and other "edible" carbohydrates.

In the farming system, sugar cane (1.5ha produces 120 tonnes stalks) supplies the energy (sugar cane juice) to feed a constant population of fattening 40 pigs. Forage trees (1 ha planted with mulberry and *Tithonia diversifolia*) provides the protein (as leaves) for 20 adult goats and progeny. The residual bagasse (18 tonnes DM/year) from the sugar cane and the stems from the forage trees (6 tonnes DM/year) are the feedstock for the gasifier. Annual outputs are 221,760 MW as producer gas and 40,150 MJ as biogas. Daily production of electricity from an IC gas engine and alternator is 54.7 Kwh from the producer gas and 8 KWh from the biogas, the total exceeding six-fold the daily electricity requirements of the farm.

Annual indirect (embedded) energy costs were estimated to be 33,205 MJ with 34% derived from human muscle power and 30% from purchased animal feeds. The output of 261,910 MJ as combustible gas results in an EROEI of 8: 1.

Key words: Biochar, biogas, EROEI, forage trees, goats, mulberry, pigs. producer gas, sugar cane

Introduction

Renewable energy from biomass and EROEI

The technologies proposed for redirecting energy from the sun into energy to replace that in fossil fuels are many. The alternatives that are currently practiced commercially (although in most cases with a high degree of Government subsidy) can be divided into processes that depend on: (i) the products of photosynthesis (eg:: ethanol produced by fermentation of sugars derived from cereal grains, cassava roots and sugar cane; and biodiesel from soya beans, rapeseed and oil palm); or (ii) that use the physical qualities of solar energy directly (photovoltaic panels, solar water heaters, windmills, tidal barrages and wave motion).

Other technologies that are frequently proposed, but not yet commercially viable, are described by Rapier (2009) as *Renewable Fuel Pretenders*. Rapier argues that their proponents believe they have a solution but that it will never develop into a feasible technology because the proponents “have no experience at scaling up technologies”. In this category he lists cellulosic ethanol, hydrogen and diesel oil from algae.

Surprisingly, gasification which is a proven technology for using biomass as a source of fuel, and which was applied widely in several "oil-dependent" countries during World War II, has received little attention from policy makers and the media. Yet, as will be shown in this paper, it appears to hold real prospects of being a sustainable technology, especially when it is applied as a component in an integrated farming system.

Hall et al (2008a, 2009) have proposed that the most appropriate way to judge the relative merits of different energy technologies is by calculating the ratio between the amount of energy produced and the energy needed to produce it, described as the EROEI (Energy Returned on Energy Invested). The EROEI in its simplest form ($EOREI_{mm}$) measures the output energy at the point of production. However, to take account of the final form in which the energy is used to support the needs of society/civilization, they proposed the term $EROEI_{ext.}$ Their indicative figures were that an EROEImm for oil of 3:1 would be sufficient to cover the energy cost of extracting the oil and the associated exploration costs for new discoveries. but that at the level of the end user (eg: to cover the needs of society/civilization), the EROEI ($EROEI_{ext}$) would need to be at least 10:1. By contrast, the $EROEI_{mm}$ for ethanol derived from maize, was estimated to be at best 1.3:1 (Cleveland et al 2006) and according to some authors (Patzek 2004; Patzek and Pimental 2006; Patzek 2007) , less than 1:1, implying that maize-based ethanol requires a "fossil" fuel, as well as a financial, subsidy.

16.2.2 Gasification as part of an integrated farming system

The concept of gasification being a partner in an integrated farming system was first developed by the senior author in 1980 when research was initiated in Mexico to develop feeding systems for pigs based on sugar juice as an alternative energy source to cereal grains. The feeding system was technically successful (Mena et al 1981), but the constraint to its development was “how to make productive use of the bagasse that accumulated as a waste product of the extraction of the juice from the sugar cane stalks". Memories of classes in chemistry at secondary school brought to mind the process of gasification, developed in the 19^{th} century, to produce combustible gas from a range of carbon-rich materials such as coal, charcoal and wood. Knowledge of the use of wood and charcoal-fueled gasifiers to propel cars and trucks in Sweden during World War 2, assisted by personal contacts with staff of the International Foundation of Science (located in Stockholm), led to the opportunity to test the use of sugar cane bagasse from Mexico as fuel in a Scania truck equipped with a wood-burning gasifier. The test took place in the city of Umea in Northern Sweden. With the close cooperation of Arne Lindgren, an engineer skilled in biogas technology, the 20 kg of sugar cane bagasse from Mexico successfully fueled the Scania truck for a 20 minute drive around the city.

It required the onset of the escalation of oil prices, twenty-three years later, to revive interest in gasification as a component of a sustainable farming system.

Fuel energy as a by-product of livestock production

Three problems associated with use of biomass as fuel are: (i) its low density (eg: from 97 to 350 kg/m^3; Miech Phalla and Preston 2005), resulting in high costs of transport if processed in a centralized utility (as with increasing distance, fossil fuel rather than animal power is needed); (ii) the cost when it is the sole product of the cropping system; and (iii) the potential conflict if land presently devoted to food crops is diverted to production of biomass for fuel.

These problems do not arise if the biomass is used at the point of production and it is the byproduct of crops that are grown primarily for human food or animal feed.

Hypothesis

The hypothesis underlying the present study is that the production of a combustible gas from biomass (gasification), when conducted as part of an integrated farming system involving live stock, will have a much higher EROEI, and be more environmentally friendly, than other biomass-based technologies and especially ethanol production from maize and other "edible" carbohydrates.

Materials and methods

Location

The study was done in the farm " TOSOLY , located at 1500msl in the Santander department of Colombia, approximately 250 km north of the capital Bogotá.

The gasifier

A 10KW gasifier (Model WBG-10) (Photo 1) was imported from Ankur Scientific Energy Technology Pvt. Ltd, in India. It was connected to a diesel engine modified to operate in 100% producer gas mode with a 230v, 3-phase alternator to give gross output of about 9 kWe. The related accessories, and mode of operation, were described by Miech Phalla and Preston (2005) and Rodríguez and Preston (2009).

Photo 1. The "Ankur" gasifier in TOSOLY farm

The farming system

The farm (Figure 1) extends to 7 ha of which 1.22 ha are in natural forest, 1.44 ha in Arabica coffee grown under shade from "Guamo" (*Inga hayesii* Benth) trees, 1.5 ha in sugar cane, 0.50 ha in permanent plantations of forage trees (mainly Mulberry [*Morus alba*] and Tithonia [*Tithonia diversifolia*] and 0.30 ha in New Cocoyam (*Xanthosoma Sagittarius*). The remaining 2 ha are accounted for by areas under citrus, bamboo (Guadua), pasture, fish ponds, roads and buildings.

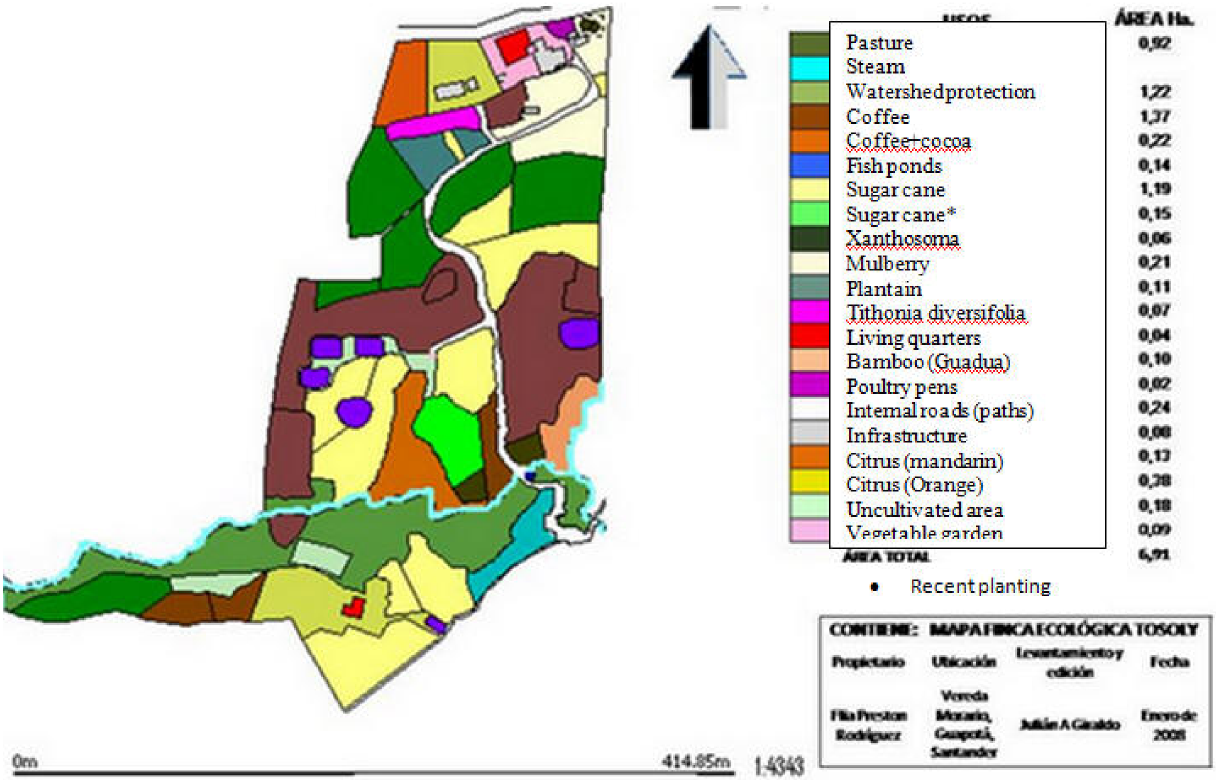

Figure 1. Map of the TOSOLY farm

For the purposes of this study the components of the farm devoted to combined feed and fuel production are sugar cane and the forage trees (Figure 2).

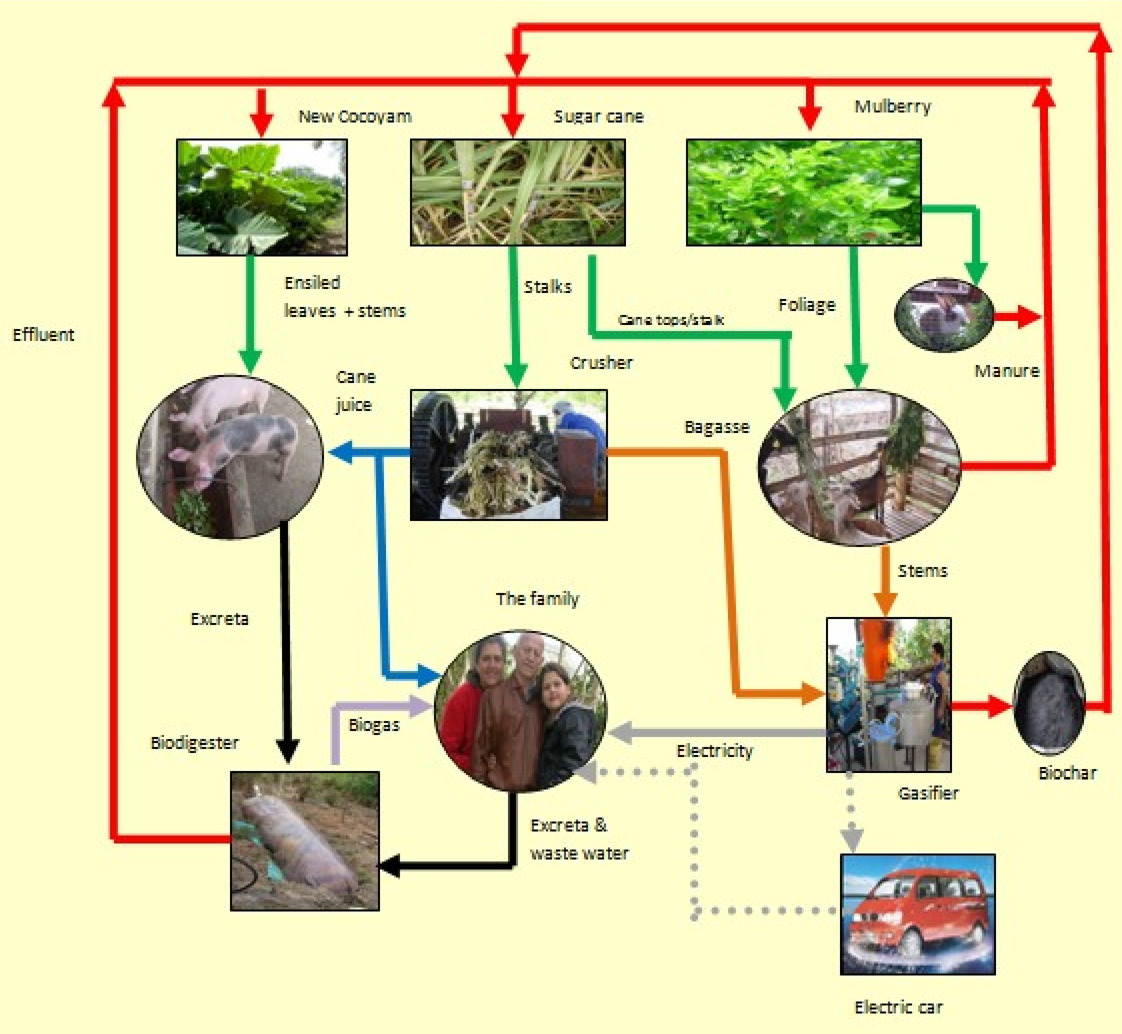

Figure 2. Flow diagram of the principal activities in the TOSOLY farm

Sources of biomass

The whole sugar cane plant is harvested and the tops (leaves + growing point) separated from the stalk, which is then passed twice through a 3-roll crusher(*trapiche*). The extracted juice is the dietary energy source for pigs (n=40); the " tops" are chopped prior to feeding them as the energy source for the goats. The bagasse (the fibrous residue after juice extraction) represents from 35 to 40% of the fresh weight of the cane stalk and contains from 55 to 65% moisture. It is sun-dried during 1 to 2 days to a moisture content of about 15%. The large pieces are presently separated and used as litter for the goats; the remaining smaller particles (1 to 3 cm) being stored for use as fuel in the gasifier (Photo 2).

The Mulberry and Tithonia trees are harvested at 6 to 8 week intervals, removing all the fresh biomass after cutting about 50 cm above soil level. The mixed foliages are fed immediately to the goats, that preferably select the Mulberry of which they eat the leaves and the rind that is completely from the stems (Photo 3).

Photo 2. Fine bagasse on the left for the gasifier; coarse particles are used as litter for goats and cattle but could be chopped and used in the gasifier

Photo 3. Mulberry foliage on the left (most of the rind on the stems has been eaten); Tithonia on the right

For the Tithonia only the leaves are eaten; the stems are left with the rind untouched (Photo 3). The stems of both trees that are not eaten by the goats (Photo 4) are collected, passed through a high speed (3500rpm) chopper (driven by a 3KW electric motor which receives power from the gasifier-alternator) and sun-dried to15% moisture for later use in the gasifier.

Photo 4. Residual stems left by the goats; the white stems (without the rind) are from the Mulberry; the green ones with leaves attached are from the Tithonia

Measurement of the EROEI

The coefficients for the indirect energy cost of inputs to the farming system, such as machinery, steel, cement, polyethylene (for the biodigesters) and animal feed, are taken from several sources (Table 1). All wastes are recycled. Those of organic origin (excreta from pigs and people; washings from coffee processing, and household activities) are the feedstock for "plug-flow" , tubular polyethylene biodigesters (Photo 5), All agricultural activities are done by oxen (land preparation) or a horse (transport; Photo 6) or by hand labor (planting, weeding and harvesting). No chemicals are used and fertilizer and organic matter are derived from recycled goat and cattle manure, the effluent from the biodigesters and "biochar" from the gasifier (Rodríguez et al (2009). The only purchased feeds for the animals are rice polishings, fish meal and minerals (calcium carbonate, rock phosphate, salt and sulphur).

Photo 5. Tubular polyethylene biodigester charged with pig manure and water

Photo 6. New Cocoyam leaves+petioles transported by "Mariscal" in TOSOLY farm

Table 1. Coefficients for energy use

Energy coefficients	Working life, yr	Weight, kg	MJ/kg
Sugar cane crusher	30	200	120[1]
Diesel engine	20	200	120[1]
Forage chopper	20	200	120[1]
Gasifier/gas engine, alternator	20	500	120*
Diesel fuel			40
Cement	50		4.5
Reinforcing steel	50		120[1]
Galvanized sheet	20		120[1]
Polyethylene	5	100	45[2]
Rice bran		6000	0.320[3]
Soybean meal		1500	5.6[3]
Minerals		100	
Other coefficients			
Energy in producer gas			*4.2 MJ/m^3
Gas from gasification of bagasse/tree stems			*2.2 m3 gas/kg DM
Energy in gas from bagasse/tree stems			9.24 MJ gas/kg DM
Energy in biogas			20 MJ/m^3
Bagasse from 1.5 ha sugar cane			18 tonnes DM/yr
Tree stems from 1 ha mulberry/tithonia			6 tonnes DM/yr

[1] *mean of values given by Pimental 1980 (109MJ/kg) and* ***Mikkola and Ahokas*** *2010 (130 MJ/kg)*
2 *Pimental 1980*
3 *LEAD (no date)*
* *from* Jorapur and Rajvanshi 1997

The input-output data from the gasifier (Table 2) were taken from the studies of Miech Phalla and Preston (2005) and Rodríguez and Preston (2009). These were extrapolated to represent the inputs from 1.5 ha of sugar cane (annual yield of 80 tonnes stalk cane) and 1 ha of forage trees (annual yield of 6 tonnes/ha of air-dry stems [15% moisture] and outputs when the bagasse and tree stems were used as feedstock in the gasifier.

EROEI (Energy Return on Energy Invested)

The coefficients used in the calculation of the EROEI are in Table 2. The calculation of the EROEI is in Table 3. If the energy output of the gasifier is based on the calorific value of the producer gas then the EROEI is 63. On the other hand, if the output is measured at the point of usage (eg: as electricity) then the EROEI decreases to 15.

The major component in the fossil energy inputs is the soybean meal. This will eventually be replaced by New Cocoyam silage and yeast-enriched sugar cane juice, produced on the farm.

It is understood that there are some energy costs not accounted for. Apart from the fish meal and rice bran used to supplement the sugar cane juice, fed to the pigs, the animals on the farm are fed almost exclusively on the `products of photosynthesis. The farm workers mostly consume food grown on the farm or in the immediate rural area. There will be additional energy costs in the (small) proportion of the food transported into the area and in the services used by the people providing manual labor (eg: their use of grid electricity, health services, road maintenance and other services).

Table 2. Calculation of the EROEI (Energy Return on energy Invested)

	Inputs	Input MJ/year	Source	Outputs MJ/year	KWh
Sugar cane/trees					
Land preparation	Oxen		Photo synthesis		
Planting	Human		Photo synthesis		
Fertilizer	Recycled manure		Photo synthesis		
Weeding	Human		Photo synthesis		
Chemicals	None		Photo synthesis		
Harvesting	Human		Photo synthesis		
Total human input	4000hr	11200	Photo synthesis[1]		
Transport	Horse/mule		Photo synthesis		
Process sugar cane	Sugar cane crusher	1200	Fossil fuel		
Process sugar cane	Diesel engine	1200	Fossil fuel		
Process sugar cane	100 ml diesel daily[2]	1460	Fossil fuel		
Process tree stems	Forage chopper	1200	Fossil fuel		
Process leaves	Goats		Photo synthesis		
Producer gas	Gasifier	3000	Fossil fuel		
Feedstock	Bagasse		Photo synthesis	166320	15000
Feedstock	Tree stems		Photo synthesis	55440	5000
Feedstock	Pig manure			40150	2920
Purchased feed					
Rice bran	5000 kg	1600	Fossil fuel		
Soybean meal	1500kg	8400	Fossil fuel		
Minerals	100kg		Fossil fuel		
Buildings					
Reinforcing steel	500kg	1200	Fossil fuel		
Cement	2.5 tonnes	225	Fossil fuel		
Galvanized iron sheets	300kg	1800	Fossil fuel		
Polyethylene plastic film	80 kg	900	Fossil fuel		
	Totals	33205		261910	22920

[1] Assumes 5600 MJ/year for each of two full-time farm workers
[2] In dual fuel mode; 75 % producer gas

Results

The combined activities of gasification and biodigestion using 24 tonnes of fibrous byproducts (bagassse + trees stems) from 1.5 ha of sugarcane and 1 ha of forage trees, and the excreta from 40 pigs and a family of two adults and one adolescent, yield a total of 261,910 MJ/year (Table 3; Figure 3). The inputs have an inbuilt energy cost as fossil fuel of 33,205 MJ/year (Figure 4). The resultant EROEI is 7.9.

Table 3. Calculation of the EROEI (Energy Return on Energy Invested)

Inputs	MJ	Outputs	MJ	EROEI
Machinery	6600	Producer gas	221760	
Human power	11200			
Diesel oil	1460	Biogas	40150	
Animal feed	10000			
Construction	4125			
Totals	**33205**		**261910**	**7.9**

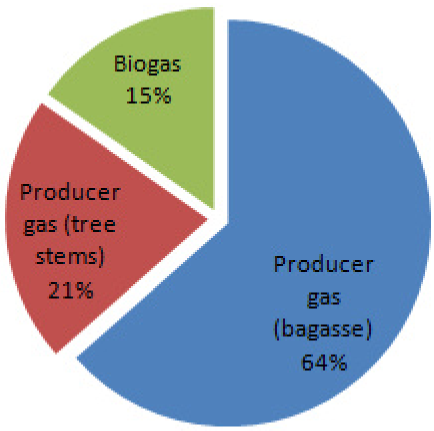

Figure 3. Outputs of combustible gas energy (% of total MJ)according to the source

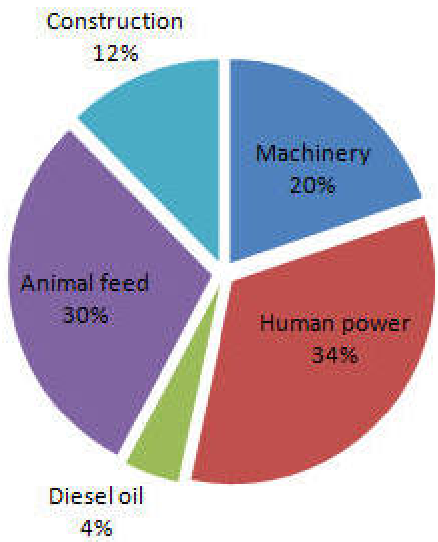

Figure 4. Inputs of inbuilt fossil fuel energy (% of total MJ) according to the source

Discussion

On-farm energy production and EROEI

The results of the study indicate that gasification of fibrous crop residues (from 1.5 ha of sugar cane and 1 ha of forage trees) together with anaerobic biodigestion of excreta from 40 fattening pigs and a family of three persons, can deliver annually 256 thousand MJ of combustible gas (equivalent to 6.4 tonnes of oil) - with an EROEI of about 8. This is much higher than has been reported for other biofuels derived from biomass (see Hall et al 2009).

The normal consumption of electricity on the farm is of the order of 5 to 10 KWh daily. The daily consumption of sugar cane juice for the pig unit (n=40) is of the order of 200 litres daily which requires the crushing of 330 kg of cane stalks daily. With an annual yield of 80 tonnes stalks/ha, the requirement is for 120 tonnes of sugar cane stalks to be produced from 1.5ha. The daily production of bagasse is therefore 50 kg (DM basis) sufficient to produce about 41 KWh of electricity daily. From the 1 ha of forage trees needed for the goat unit, the yield of dry stems is estimated at 6000 kg/ha/year, producing a further 13.7 KWh. - a total of 54.7 KWh per day. This would provide a surplus at the farm of the order of 45 to 50 KWh daily that could be fed into the regional electricity grid or used directly for activities in the local community such as (in the future!) the charging of the batteries of electric vehicles. The gas produced from the biodigesters (about 5 m^3 daily) is surplus to the needs for cooking and perhaps 50% could be used for electricity generation which would generate a further 4 KWh of electricity daily.

The EROEI of 8 is more than twice the EROEI (3:1) for oil and six times that for maize-based ethanol (1.3:1) according to data from Hall et al (2008b).

The major part of the energy inputs not derived from solar energy relate to human muscle power and the purchase of animal feed (Figure 4). Production of soybean meal has a relatively high inbuilt energy cost (5.6MJ/kg). It is planned to replace this protein-rich feed by increasing the area for growing New Cocoyam and producing a high protein supplement on the farm by artisan production of fodder yeast from the cane juice. Replacing the imported animal feed by locally produced alternatives would raise the EROEI to 11. The two people working on the farm will have some embedded fossil fuel attached to their contribution as muscle power. In their calculation of the energy costs of ethanol from maize, Pimental and Patzek (2005) assumed a figure of 8000 litres oil per person in USA working 2000 hours per year. This is the equivalent of 52 barrels of oil per person per year!!. It is suggested that the embodied oil cost of a farm worker in rural Colombia is closer to 1 barrel of oil/year, similar to the average for China. Farm workers in rural Colombia do not have a car, they walk to work, rarely take vacations, consume mostly what is grown locally and have limited access to public services (eg: access roads are unpaved, infrequent or no garbage collection, septic tanks for sewage....). There is an obvious need for detailed analysis of this component, which will be very "location-specific".

The next highest source of indirect energy costs is incurred in the manufacture of the machinery which accounts for 20% of the total fossil fuel inputs. The steel, which is the main component in the machinery being used on the farm, can be recycled at the end of the working life, and as such will have a relatively energy over "new" as the energy cost of the steel is mostly incurred in the mining and processing of the ore. Making an allowance for this component would further raise the EROEI.

Carbon sequestration and soil fertility - other benefits from gasification

The gasification of fibrous biomass produces a carbon-mineral residue known as "biochar". The quantities produced appear to depend on the nature of the biomass being gasified and the operating conditions of the gasifier. In the specific case of sugar cane bagasse and tree stems in the gasifier in TOSOLY, the production of biochar was recorded as 8.5 and 11.7% of the input of bagasse and tree stems, respectively (Rodríguez Lylian, 2009, unpublished data). Converting this to a dry matter basis raises the yield to 10 and 14%, which is similar to the values reported by Miech Phalla amd Preston (2005) for a range of fibrous crop residues/byproducts processed in the same type of gasifier.

Biochar has been shown to be an excellent conditioner for the acid soils that predominate in the humid tropics (Rodríguez et al 2009). The growth rate of maize in acid soils from the

TOSOLY farm was increased five-fold by application of the equivalent of 50 tonnes/ha of biochar derived from bagasse. It is also expected that most of the carbon in the biochar will be permanently sequestered when incorporated in the soil (Lehmann 2007). From the 50 kg of bagasse derived daily from 330 kg/day of sugar cane stalks and the 16 kg of stem DM from the 130 kg of tree foliage, the daily production of biochar will be 6.6 kg of which 4.4 kg will be carbon. In one year this is 1.6 tonnes of carbon (6 tonnes of CO_2) sequestered annually (3 tonnes CO_2/ha/year). At the same time, each year, the biochar will act as soil conditioner sufficient to ameliorate 0.24 ha of crop area, assuming an application rate of 20 tonnes/ha (Rodriguez Lylian and Preston T R , Unpublished data). Thus in 6 years, the whole of the sugar cane and tree foliage area could be treated with biochar, The benefits in terms of reduced fertilizer needs have yet to be quantified but appear to be considerable (see Rodriguez et al 2009).

Conclusions

- The EROEI of 8 for the production of a combustible gas from sugar cane bagasse and tree stems appears to be considerably higher than has been reported for other technologies for deriving biofuels from biomass.
- There are other associated benefits from the technology such as the production of biochar as a soil ameliorator and means of sequestering carbon.
- The favourable EROEI of the system reflects the minimum use of external sources of energy, which is made possible by the integrated, mixed farming strategy in which most of the required inputs are produced on the farm.

Acknowledgements

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Chapter 11. General discussion

The overall aim of this thesis was to provide data that would contribute to the development of sustainable farming systems in the tropics, against a background of the triple world crises of resource depletion, especially oil, climate change and economic recession. It is argued that in order to respond to these pressures, future farming systems must produce not only food for people and feed for animals, but also energy that will perform useful tasks on the farm, with surplus supplies being channelled into the electrical grid or for the use of local communities. These objectives should be met within a framework of activities that ensures an overall negative carbon footprint. Responding to the energy crisis not only requires the development of renewable sources of energy. The efficiency of using energy must also be increased as there is no alternative form of energy that can replace fossil fuels at the present rate of usage.

Chapter 1 is a discussion of the issues that should determine the strategy underlying the need to develop appropriate farming systems in the face of resource depletion, climate change and the failure of the model of market economics. On the basisof this discussion, it was hypothesized that the areas to be researched should relate to evaluation of the nutritive value of locally-grown feed resources, the need to “de-carbonize” the system by reducing emissions of greenhouse gases, generating electricity locally from natural resources, making maximum use of solar energy and ensuring there would be no conflict between theuse of available resources for both food and fuel production.

It was not possible to carry out experiments on all the components of the farming system shown in the introduction (Chapter 1; Figure 1). The decision was made to study those features which were least researched as new information in these areas could be expected to have greatest impact on the sustainability of the system and on the potential to provide options for future farming practices. The research has been done in a "real farming system" so the "real needs" directed the aims of the thesis. The areas researched were crucial areas to be developed and improved in the system. Today the farming system is improved and it is clear the need to continue doing research to make it more sustainable from the technical, environmental and social point of view.

For these reasons, the components that were chosen as subjects to be researched were:

- The nutritional value of the foliage of New Cocoyam (*Xanthosoma sagittarius*) as a replacement for soybean meal in diets of growing pigs (Chapters 3, 4 and 5))
- The biochar produced as a byproduct of the gasification of the bagasse as a soil amendment (Chapter 6)
- Agronomic studies to measure the biomass yield of New Cocoyam (Chapter 7)
- Ensiling the combined leaves and petioles of New Cocoyam (Chapter 8)
- The gasification of sugar cane bagasse and stems of forage trees (Chapter 9)
- Measuring the EROEI for production of electricity by gasification of sugar cane bagasse (Chapter 10)

Sugar cane and foliages from trees and crop plants as feed resources for live stock and as sources of renewable energy

The rationale for investigating these resources is based on several premises.

Localization of production

The first premise is the need to develop farming systems that utilize resources that can be grown on the farm with minimal need for external sources of energy. Transport presently accounts world-wide for some 30% of fossil fuel use and is a major component of the embodied energy in purchased feeds. This cost can be avoided to a major extent if feeds and energy are produced on the farm.

Farm size

If the farm size is relatively small (4 to 7ha), the use of animal traction instead of machines is much more feasible; and the recycling of livestock manure is facilitated. There are also social benefits when the workers are also the owners, as is possible in the “family” farm. The farm most be seen as part of a community of small scale farmers. The integrated system requires an "integrated teamwork". The system per se requires special people in terms of commitment and enthusiasm, requires capable people which does not necessarily mean people with high level of education. It is clear that, on balance, the capacity to learn by doing and learn by living counts more than the degree of education. The system needs leadership and understanding of the global issues to be able to act locally. The system must promote integration with neighbors to be able to accomplish the different tasks in the farm. The system is projected to encompass family and community development.

Efficient capture of solar energy

If it is accepted that solar energy is the only sustainable source of energy, then farming systems must be designed to maximize the rate of capture of this resource. Forty years ago, Kormondy (1970) pointed out the advantages for biomass production of tropical latitudes and of perennial crops and forest compared with annual crops (Figure 1). Similar contrasts were highlighted by Patzek (2007; Figure 2). In the latter case the contrast between pastures and crops and forests is especially noteworthy. The decision to base the cropping system in the TOSOLY farm on sugar cane and trees has thus a firm ecological basis.

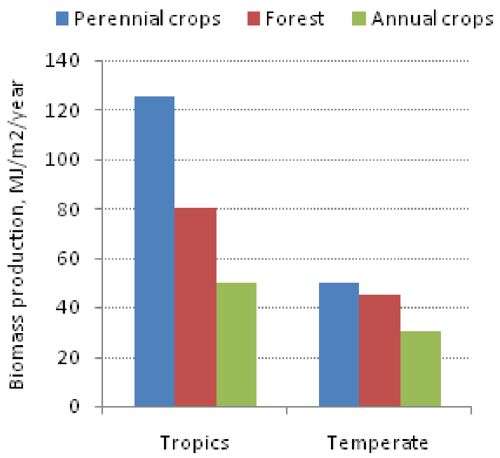

Figure 1. Net biomass production from different ecosystems (Kormondy 1970)

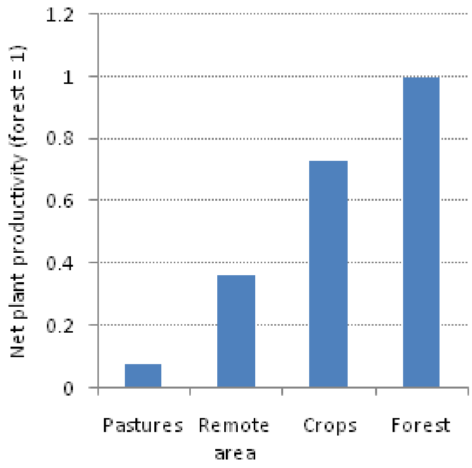

Figure 2. Net plant productivity of different ecosystems in the USA (adapted from Patzek 2007)

Apart from being perhaps the most efficient known plant for capturing solar energy, sugar cane has many other advantages, linked specifically with the thesis expounded in Chapter 1, of the need to produce both food/feed and fuel energy in an integrated farming system. The ease of separating sugar cane stalk into juice (from which sugar was produced) and residual fibre (the bagasse used as fuel to evaporate the water) was exploited five centuries ago by European colonialists in the Caribbean. The fact that the juice contains no fibre and is 100% digestible was the reason to develop it as the preferred energy source for pig feeding in the tropics (Mena et al 1981), as it was hypothesized that the absence of fibre would facilitate incorporation in the pig diet of high yielding protein-rich foliages, the fibre content of which would have been a limiting factor if combined with conventional energy sources from cereal grains. The use of the bagasse as a source of "biofuel" was shown at that time to be technically feasible but economically unattractive in a world driven by cheap petroleum and natural gas (Chapters 9 and 10).

New Cocoyam (Xanthosoma sagittifolium)

Using the fresh leaves as a protein source for growing pigs

The appreciation of the potential role of New Cocoyam (known locally as "Bore"or "Malanga") in the TOSOLY integrated farming system was accidental. Initial attempts to grow and use cassava foliage as the protein-rich forage to accompany the sugar cane juice proved to be a failure in that at 1500 masl the plant would not survive the repeated harvesting that had proved successful at <20 masl in Vietnam and Cambodia (Preston 2001). Bore was found growing wild in the humid natural forest area of the farm. Observations on the pigs offered the leaves of New Cocoyam showed it to be highly palatable and led to the experiment described in Chapter 3 (Rodríguez et al 2006) in which 50% of the protein normally supplied by soybean meal was replaced by fresh leaves of New Cocoyam with no reduction in pig performance rates compared with the control diet of 100% of the protein from soybean meal (Rodríguez et al 2006).

The experiment described in Chapter 4 (Rodríguez et al 2009a) aimed to explore the effects on parameters of apparent digestibility and N retention in young growing pigs of 100% replacement of the soybean protein by New Cocoyam leaves. In this trial the leaves were homogenized in a blender along with sugar cane juice to facilitate feeding and to avoid wastage in the metabolism cage. DM intakes were high (5% of live weight) and similar with substitution rates of soybean protein up to 53% and even with 100% substitution intakes were only reduced by some 7%. The major effect was a substantial linear decline in the digestibility of the protein (by 25% on 100% substitution) as the substitution with New Cocoyam leaves was increased, and a resultant linear decrease in N retention of about 25% at the 100% substitution level. There was, however, a compensatory response in that N excreted in the urine decreased linearly with level of New Cocoyam leaves with the overall result that the N retention as a percentage of N digested favoured the diets with increasing proportions of New Cocoyam leaves. That the digestibility of the protein was the limiting nutritional factor in the New Cocoyam leaves was indicated by the fact that, when the data were corrected for intakes of digestible protein, N retention was similar (6.9, 8.0, and 8.0 g.day for diets with 0, 53 and 100% protein substitution by New Cocoyam leaves) and higher (9.0 g/day) for the diet with 25% substitution.

Using the ensiled leaves as a protein source for growing pigs

The third experiment (Chapter 5; Rodríguez et al 2009b) to determine the nutritive potential of New Cocoyam foliage took account of the experiences described in Chapter 8 and summarized in the next section, namely using the ensiled leaves in place of the fresh leaves. The aim was to determine the feasibility of using ensiled New Cocoyam leaves (ENCL) as the only protein source to balance the sugar cane juice in the diet of young growing pigs (mean initial LW of 19 kg). The experimental design was a production function with the independent variable being the level of crude protein in the range of 80 to 160 g crude protein per kg of diet DM . The levels recorded in the experiment varied slightly (87 to 149 g crude protein/kg DM) equivalent to a range in proportions of diet DM as ENCL of 46 to 67%.

The relationship between proportion of ENCL in the diet DM (X) and N retention (Y=g N/kg LW) was curvilinear with the maximum value of N retention being reached when the ENCL provided 66% of the diet DM, equivalent to a crude protein concentration of 13% in the diet DM. Intakes of DM were high on all diets with the maximum of 4.5% of LW with 55% of ENCL in the diet corresponding to a crude fibre content of 9% in the diet DM.

The experimental deign can be criticized in that the 8 different levels of ENCL were achieved by using the same 4 pigs in two consecutive periods such that there was no replication of any one chosen level. Nevertheless the results were broadly in line with theoretical expectations. The pigs easily consumed the ensiled leaves at levels (66%) which were double those (35%) reported by Leterme et al (2005) who dried and ground the leaves of New Cocoyam prior to incorporating them in a diet based on maize. The maximum pig response, as measured by N retention, was achieved with 66% of the diet in the form of ENCL. At this point the crude fiber content had reached 9% which is within the range (7-10% according to Kass et al 1980) when pig growth rates begin to be depressed, as was observed in our experiment. In the experiment of Leterme et al 2005, the basal diet contained maize, soybean meal and rice hulls, thus with only 35% of New Cocoyam leaf meal in the diet, the overall fiber level was already 8% in DM, relatively close to the level of 9% fibre with 66% ENCL in a basal diet of sugar cane juice.

In the pig feeding system described in this thesis, in which the basal diet (sugar cane juice) contains neither fibre nor protein, these two components have opposing influences on performance when foliages are used as the protein supplement. To achieve the level of protein necessary to optimize growth rates (about 13-15% in DM) results in reaching levels of crude fibre which act so as to reduce performance (eg: “the shielding effect on the plant cell contents by the indigestible cell walls, increased rates of passage of digesta as a result of its increased bulk and water-holding capacity, irritation of the gut wall mucosa by VFA produced in the hind-gut, possible presence of anti-nutritional factors, bulkiness, energy dilution and possibly heat stress” [Ogle 2006]). To increase the protein level in these diets without increasing the crude fiber content would require using protein sources such as fish meal or soybean meal, which have very little or no fibre. The final decision will depend on the relative economics of using locally-grown protein supplements as opposed to purchased supplements. Such economic considerations will depend on monetary costs and also increasingly on “embedded” (fossil) energy costs of the alternative feed resources. This aspect will be discussed in a later section of this Chapter.

Ensiling leaves and petioles of New Cocoyam

Practical experiences on the farm led to the conclusion that daily harvesting and feeding of fresh New Cocoyam leaves was not convenient from the standpoint of: (i) appropriate management of the New Cocoyam plant as leaf growth was dependent on climatic factors, which meant that daily harvesting did not always yield the required amounts of leaves, and often the leaves were harvested when they were still immature; and (ii) daily harvesting was time consuming and inefficient in the use of the horse used to transport the leaves. This led to the decision to study the ensiling of the leaves which would permit harvesting of ;leaves at the most appropriate stage of growth, from the physiological viewpoint (the leaves of New Cocoyam have similar growth cycles as leaves from banana plants, in that every 2 to 3 weeks new leaves emerge from the stem and grow until the point of senescence is reached usually some 3 to 4 weeks later). The work of harvesting and ensiling was then organized on a cycle of 20 to 25 days in accordance with the growth stage of the plants.

The studies described in Chapter 8 (Rodríguez and Preston 2009a) were initiated in order to define the most appropriate method for ensiling the New Cocoyam foliage, as there were no references to be found in the literature on ways to process and store this foliage by ensiling. The first attempt followed conventional procedures using sugar cane juice as a substitute for molasses. The ensiled leaves produced by this process had all the required qualities of low pH, attractive colour and smell and absence of mold. The problem was the considerable effort needed to mix the cane juice with the macerated leaves and then to consolidate them in the plastic container. The other problem that arose was the disposal of the petioles. It was not convenient to leave them in the field as mulch, as this would have required transporting only the leaves – a difficult operation in sloping terrain which necessitated stacking the load in the structure mounted on the horse which is the traditional way of transporting sugar cane (Photo 8.1). Attempting to accommodate only the leaves in this structure proved to be highly inconvenient and inefficient. The other option of feeding the petioles to the pigs proved to be feasible in that they were well accepted. It was also observed that ensiling the petioles, despite the high moisture content (>90%) was an effective way of conserving them; Furthermore, it was found there was no need to add additional fermentable sugars as the pH dropped to less than 4 within 48 hours. But again, the work load of separating the leaves from the petioles and macerating each of these components separately was time-consuming. Moreover, forcing the leaves into the ensiling machine was difficult. By contrast, passing the intact foliage – leaf and petiole – into the ensiling machine was easy and rapid. The logical next step was to ensile the combined leaf and petiole. This also produced excellent silage and has become the standard management system on the farm for processing New Cocoyam foliage. As was demonstrated in the experiment reported in Chapter 8, this procedure .fulfilled all the requirements for producing a uniform and nutritious product, without the need for any additive.

The observation that the juice in the petiole was high in soluble sugars (4-5% in the juice = about 25% in the DM) explained the good results obtained by incorporating the petiole with the leaf in the silage. The negative consequence – a decrease in the protein content of the mixture (the petiole contains only 7 to 8% crude protein in DM) – was compensated by the more efficient use of the plant biomass (the petioles make up some 50% of the foliage DM (Chapter 7). The other feature of the petiole in New Cocoyam is that, in contrast with many other forages, it is not heavily lignified as it is the water in the petiole which provides the main structural support for the leaves, in the same way that the pseudo-stem supports the leaves in the banana plant. Analysis of the leaves and petioles showed that the content of NDF was lower in the petioles (22.7% in DM) than in the leaves (37.8%). ADF values of 7.7 and 6.6% showed similar trends. The low content of structural carbohydrates in the petiole, together with the high content of soluble sugars, leads to the conclusion that the petiole can be considered as a potential energy source, as well as a convenient medium for facilitating the ensiling process. Some recent results from Vietnam (Figures 3 and 4) demonstrate the beneficial effects of mixing the leaf and petiole of Taro (*Colocacia esculenta*) with the pseudo-stem of banana, which can be linked to the relatively high content of soluble sugars in the Taro.

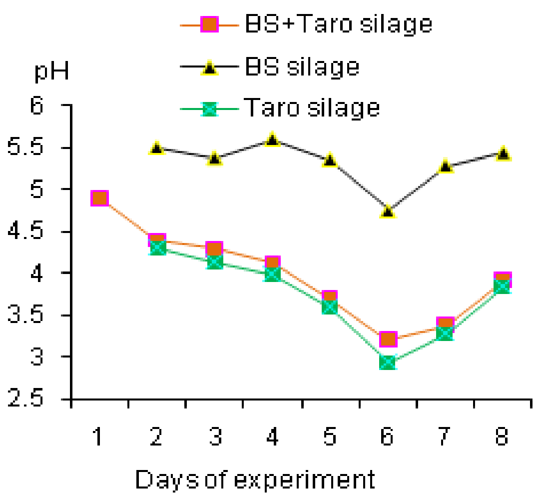

Figure 3. Pattern of pH change in ensiled banana pseudo-stem (BS) with and without incorporation (50:50 fresh basis) of taro foliage (changes in the pH of Taro silage are also shown) (Dao Thi My Tien et al 2010)

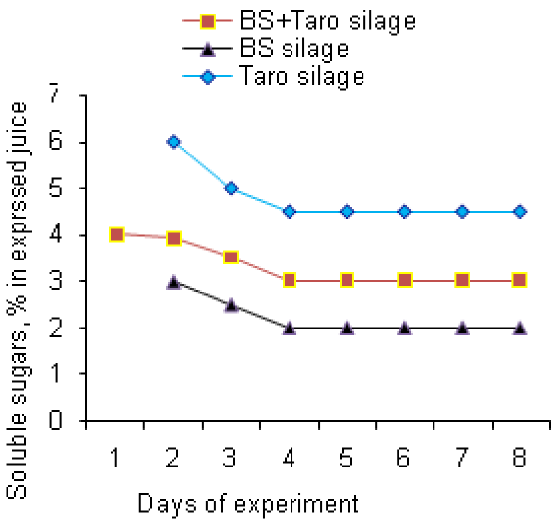

Figure 4. Change of soluble sugars in ensiled banana pseudo-stem (BS) with and without incorporation (50:50 fresh basis) of taro foliage (changes in Taro silage are also shown) (Dao Thi My Tien et al 2010)

Biomass productivity of New Cocoyam

The research described in Chapter 7 (Rodríguez and Preston 2009b) was a first attempt to generate information on the agronomic features of the New Cocoyam plant. The results showed clearly the advantages of establishing the plant from suckers (emerging new shoots) than from sections (disks) taken from the stem. The predicted annual per ha yields, in acid soils of low fertility, of 14.5 and 1.90 tonnes of DM and crude protein, respectively, show that the plant is efficient in capturing solar energy. With higher and more evenly spaced fertilization (eg: from biodigester effluent) it can be expected that the yield potential will be much greater.

On the basis of the above yields and assuming that 10% of the crude protein needs are supplied by a high protein supplement such as fish meal, soybean meal or locally produced yeast, then the area planted to New Cocoyam should be 1.5 ha, the same as sugar cane to provide feed for an average population of 50 pigs.

Gasification of sugar cane bagasse and stems of forage trees

It is apparent from the research described in Chapters 9 (Rodríguez and Preston 2009c) and 10 (Preston and Rodríguez 2010) that supplying the electricity needs of the farm could be met from gasification of less than 20% of the available fibrous biomass residues from 1.5ha of sugar cane and 1 ha of forage trees. This raises the question of how to use the surplus electricity (about 35 KWh daily). Schemes for feeding the energy into the local electricity grid are on-going in cities in Europe, USA and Japan (see Box 1).

Box 1. Beginning March 1 2009, those in Gainesville, Florida USA, with new solar photovoltaic systems will be eligible to receive 32 cents per kilowatt hour of electricity produced by the system over the next 20 years. http://www.gainesville.com/article/20090206/ARTICLES/902061014?Title=Commission-gives-its-approval-to-feed-in-tariff-for-solar-power

At USD 0.30/KWh, the daily surplus of electricity (about 35KWh) from 2.5 ha of cropland would be worth USD10.5, about USD 3,650 per year. Another alternative (in the future!) is to support directly the local community by developing a facility for charging the batteries of electric vehicles.

The important feature of the system is that food/feed production is not compromised as both feedstocks represent components of the respective crops which have no value as feed or food.

Energy Returned Over Energy Invested (EROEI)

The analysis of energy gained as a combustible gas as a function of the equivalent fossil fuel energy embedded in the various farm activities indicated an EROEI of about 8 which according to Hall et al (2009) more than provides for the needs of society (estimated by these authors as an EROEI of the order of 5). .There is an urgent need to develop this information which would facilitate the calculation of more precise estimates of the EROEI of integrated food-feed-energy production in a small scale farming system.

Biochar for the Mitigation of Greenhouse Gas Emissions and as a Soil Conditioner

The biochar produced by gasification promises to have multiple uses, most of which are still relatively unexplored. The degree to which it it is a sink for sequestering carbon in the soil is the subject of numerous claims (see Lehman 2007), based almost entirely on the observations made in the Amazon of carbon-rich "terra preta" soils formed by indigenous tribes thousands of years ago (Glaser 2007). Assuming the figure of 2 tonnes of carbon dioxide sequestered per ha of land cropped for integrated food-feed-energy production (Chapters 8 and 9) , and that there is a potential 3 billion ha of arable land available (OECD/FAO 2009), the biochar produced on this land area would permit the sequestration of 6 billion tonnes of carbon dioxide. Present world annual emissions of carbon dioxide are estimated to be 24 billion tonnes (http://en.wikipedia.org/wiki/List_of_countries_by_carbon_dioxide_emissions). Thus if every ha of crop land in the world was managed for integrated food-feed-energy the potential to sequester carbon dioxide is about 25% of present world emisions.

According to the US Energy Administration Agency (http://www.eia.doe.gov/iea/elec.html), world electricity generation in 2006 was 18 trillion KWh. Taking the figure of 20KWh/ha/day (Chapter 9), then on a world basis this represents a potential annual production of about 21 trillion KWh, quite close to the recorded output in 2006.

Obviously not all the world arable land would be suitable for the integrated farming system of the type described in Chapter 1. Nevertheless, there is obviously considerable potential for sequestering carbon and producing electricity from biomass without compromising food production and almost certainly with attendant gains in soil fertility and with positive effects on the environment.

Conclusions

The likely impacts from the research described in this thesis are:

- The ensiled foliage (combined leaves and petioles) of the New Cocoyam plant (*Xanthosoma sagittifolia*) offer a high degree of promise as a protein-rich forage for replacing conventional protein sources in diets for pigs
- Integrated, small scale, farming systems based around multi-purpose crops and live stock, can provide food, feed with no conflict among these end uses
- Gasification of fibrous crop residues produces electricity and a soil conditioner (biochar) that is also a sink for sequestration of atmospheric carbon. Biogestion of all liquid wastes produces a gaseous fuel for cooking with alternative use as a complement to the gaseous fuel from the gasifier.
- The system delivers real benefits for the environment (a negative carbon footprint) through carbon sequestration and improvements in soil fertility.

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